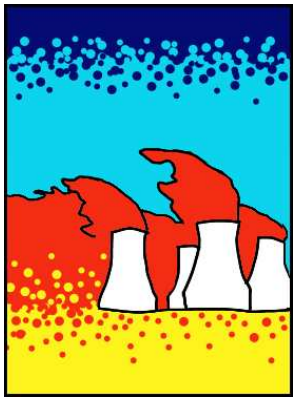
Part II

Making a difference



19 Every BIG helps

"We were going to have a wind turbine but they're not very efficient"

Figure 19.1. Reproduced by kind permission of PRIVATE EYE / Robert Thompson `www.private-eye.co.uk`.

We've established that the UK's present lifestyle can't be sustained on the UK's own renewables (except with the industrialization of country-sized areas of land and sea). So, what are our options, if we wish to get off fossil fuels and live sustainably? We can balance the energy budget either by reducing demand, or by increasing supply, or, of course, by doing both.

Have no illusions. To achieve our goal of getting off fossil fuels, these reductions in demand and increases in supply must be *big*. Don't be distracted by the myth that "every little helps." *If everyone does a little, we'll achieve only a little.* We must do a lot. What's required are *big* changes in demand and in supply.

"But surely, if 60 million people all do a little, it'll add up to a lot?" No. This "if-everyone" multiplying machine is just a way of making something small *sound* big. The "if-everyone" multiplying machine churns out inspirational statements of the form "if *everyone* did X, then it would provide enough energy/water/gas to do Y," where Y sounds impressive. Is it surprising that Y sounds big? Of course not. We got Y by multiplying X by the number of people involved – 60 million or so! Here's an example from the Conservative Party's otherwise straight-talking *Blueprint for a Green Economy*:

> "The mobile phone charger averages around . . . 1 W consumption, but if every one of the country's 25 million mobile phones chargers were left plugged in and switched on they would consume enough electricity (219 GWh) to power 66 000 homes for one year."

66 000? Wow, what a lot of homes! Switch off the chargers! 66 000 sounds a lot, but the sensible thing to compare it with is the total number of homes that we're imagining would participate in this feat of conservation, namely *25 million* homes. 66 000 is just *one quarter of one percent* of 25 million. So while the statement quoted above is true, I think a calmer way to put it is:

> If you leave your mobile phone charger plugged in, it uses one quarter of one percent of your home's electricity.

And if everyone does it?

> If *everyone* leaves their mobile phone charger plugged in, those chargers will use one quarter of one percent of their homes' electricity.

The "if-everyone" multiplying machine is a bad thing because it deflects people's attention towards 25 million minnows instead of 25 million sharks. The mantra *"Little changes can make a big difference"* is bunkum, when applied to climate change and power. It may be true that "many people doing

a little adds up to a lot," if all those "littles" are somehow focused into a single "lot" – for example, if one million people donate £10 to *one* accident-victim, then the victim receives £10 million. That's a lot. But power is a very different thing. We all use power. So to achieve a "big difference" in total power consumption, you need almost everyone to make a "big" difference to their own power consumption.

So, what's required are *big* changes in demand and in supply. Demand for power could be reduced in three ways:

1. by reducing our population (figure 19.2);
2. by changing our lifestyle;
3. by keeping our lifestyle, but reducing its energy intensity through "efficiency" and "technology."

Supply could be increased in three ways:

1. We could get off fossil fuels by investing in "clean coal" technology. Oops! Coal is a fossil fuel. Well, never mind – let's take a look at this idea. If we used coal "sustainably" (a notion we'll define in a moment), how much power could it offer? If we don't care about sustainability and just want "security of supply," could coal offer that?
2. We could invest in nuclear fission. Is current nuclear technology "sustainable"? Is it at least a stop-gap that might last for 100 years?
3. We could buy, beg, or steal renewable energy from other countries – bearing in mind that most countries will be in the same boat as Britain and will have no renewable energy to spare; and also bearing in mind that sourcing renewable energy from another country doesn't magically shrink the renewable power facilities required. If we import renewable energy from other countries in order to avoid building renewable facilities the size of Wales in *our* country, someone will have to build facilities roughly the size of Wales in those other countries.

The next seven chapters discuss first how to reduce demand substantially, and second how to increase supply to meet that reduced, but still "huge," demand. In these chapters, I won't mention *all* the good ideas. I'll discuss just the *big* ideas.

Cartoon Britain

To simplify and streamline our discussion of demand reduction, I propose to work with a cartoon of British energy consumption, omitting lots of details in order to focus on the big picture. My cartoon-Britain consumes

While the footprint of each individual cannot be reduced to zero, the absence of an individual does do so.

Chris Rapley, former Director of the British Antarctic Survey

We need fewer people, not greener ones.

Daily Telegraph, 24 July 2007

Democracy cannot survive overpopulation. Human dignity cannot survive overpopulation.

Isaac Asimov

Figure 19.2. Population growth and emissions... Cartoon courtesy of Colin Wheeler.

energy in just three forms: heating, transport, and electricity. The heating consumption of cartoon-Britain is 40 kWh per day per person (currently all supplied by fossil fuels); the transport consumption is also 40 kWh per day per person (currently all supplied by fossil fuels); and the electricity consumption is 18 kWh(e) per day per person; the electricity is currently almost all generated from fossil fuels; the conversion of fossil-fuel energy to electricity is 40% efficient, so supplying 18 kWh(e) of electricity in today's cartoon-Britain requires a fossil-fuel input of 45 kWh per day per person. This simplification ignores some fairly sizeable details, such as agriculture and industry, and the embodied energy of imported goods! But I'd like to be able to have a *quick* conversation about the main things we need to do to get off fossil fuels. Heating, transport, and electricity account for more than half of our energy consumption, so if we can come up with a plan that delivers heating, transport, and electricity sustainably, then we have made a good step on the way to a more detailed plan that adds up.

Having adopted this cartoon of Britain, our discussions of demand reduction will have just three bits. First, how can we reduce transport's energy-demand and eliminate all fossil fuel use for transport? This is the topic of Chapter 20. Second, how can we reduce heating's energy-demand and eliminate all fossil fuel use for heating? This is the topic of Chapter 21. Third, what about electricity? Chapter 22 discusses efficiency in electricity consumption.

Three supply options – clean coal, nuclear, and other people's renewables – are then discussed in Chapters 23, 24, and 25. Finally, Chapter 26 discusses how to cope with fluctuations in demand and fluctuations in renewable power production.

Having laid out the demand-reducing and supply-increasing options, Chapters 27 and 28 discuss various ways to put these options together to make plans that add up, in order to supply cartoon-Britain's transport, heating, and electricity.

I could spend many pages discussing "50 things you can do to make a difference," but I think this cartoon approach, chasing the three biggest fish, should lead to more effective policies.

But what about "stuff"? According to Part I, the embodied energy in imported stuff might be the biggest fish of all! Yes, perhaps that fish is the mammoth in the room. But let's leave defossilizing that mammoth to one side, and focus on the animals over which we have direct control.

So, here we go: let's talk about transport, heating, and electricity.

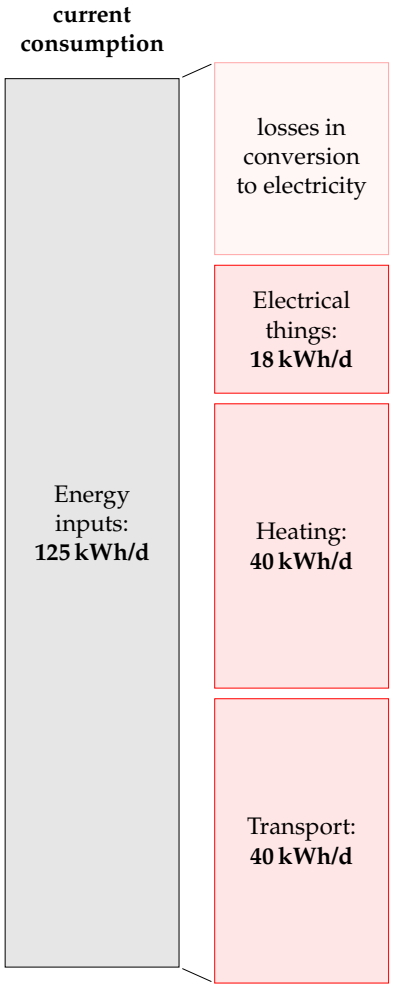


Figure 19.3. Current consumption in "cartoon-Britain 2008."

For the impatient reader

Are you eager to know the end of the story right away? Here is a quick summary, a sneak preview of Part II.

First, we electrify transport. Electrification both gets transport off fossil fuels, and makes transport more energy-efficient. (Of course, electrification

increases our demand for green electricity.)

Second, to supplement solar-thermal heating, we electrify most heating of air and water in buildings using *heat pumps*, which are four times more efficient than ordinary electrical heaters. This electrification of heating further increases the amount of green electricity required.

Third, we get all the green electricity from a mix of four sources: from our own renewables; perhaps from "clean coal;" perhaps from nuclear; and finally, and with great politeness, from other countries' renewables.

Among other countries' renewables, solar power in deserts is the most plentiful option. As long as we can build peaceful international collaborations, solar power in other people's deserts certainly has the technical potential to provide us, them, and everyone with 125 kWh per day per person.

Questions? Read on.

20 Better transport

Modern vehicle technology can reduce climate change emissions without changing the look, feel or performance that owners have come to expect.

California Air Resources Board

Roughly one third of our energy goes into transportation. Can *technology* deliver a reduction in consumption? In this chapter we explore options for achieving two goals: to deliver the biggest possible reduction in transport's energy use, *and* to eliminate fossil fuel use in transport.

Transport featured in three of our consumption chapters: Chapter 3 (cars), Chapter 5 (planes), and Chapter 15 (road freight and sea freight). So there are two sorts of transport to address: passenger transport, and freight. Our unit of passenger transport is the passenger-kilometre (p-km). If a car carries one person a distance of 100 km, it delivers 100 p-km of transportation. If it carries four people the same distance, it has delivered 400 p-km. Similarly our unit of freight transport is the ton-km (t-km). If a truck carries 5 t of cargo a distance of 100 km then it has delivered 500 t-km of freight-transport. We'll measure the energy consumption of passenger transport in "kWh per 100 passenger-kilometres," and the energy consumption of freight in "kWh per ton-km." Notice that these measures are the other way up compared to "miles per gallon": whereas we like vehicles to deliver *many* miles per gallon, we want energy-consumption to be *few* kWh per 100 p-km.

Figure 20.1. This chapter's starting point: an urban luxury tractor. The average UK car has a fuel consumption of 33 miles per gallon, which corresponds to an energy consumption of 80 kWh per 100 km. Can we do better?

We'll start this chapter by discussing how to reduce the energy consumption of surface transport. To understand how to reduce energy consumption, we need to understand where the energy is going in surface transport. Here are the three key concepts, which are explained in more detail in Technical Chapter A.

1. In *short-distance travel* with lots of starting and stopping, the energy mainly goes into speeding up the vehicle and its contents. Key strategies for consuming less in this sort of transportation are therefore to *weigh less*, and to *go further between stops*. Regenerative braking, which captures energy when slowing down, may help too. In addition, it helps to *move slower*, and to *move less*.

2. In *long-distance travel* at steady speed, by train or automobile, most of the energy goes into making air swirl around, because you only have to accelerate the vehicle once. The key strategies for consuming less in this sort of transportation are therefore to *move slower*, and to *move less*, and to *use long, thin vehicles*.

3. In all forms of travel, there's an energy-conversion chain, which takes energy in some sort of fuel and uses some of it to push the vehicle

forwards. Inevitably this energy chain has inefficiencies. In a standard fossil-fuel car, for example, only 25% is used for pushing, and roughly 75% of the energy is lost in making the engine and radiator hot. So a final strategy for consuming less energy is to make the energy-conversion chain more efficient.

These observations lead us to six principles of vehicle design and vehicle use for more-efficient surface transport: *a*) reduce the frontal area per person; *b*) reduce the vehicle's weight per person; *c*) when travelling, go at a steady speed and avoid using brakes; *d*) travel more slowly; *e*) travel less; and *f*) make the energy chain more efficient. We'll now discuss a variety of ways to apply these principles.

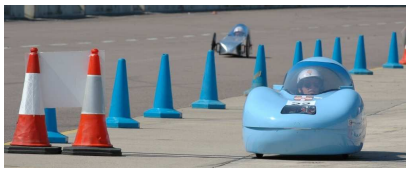


Figure 20.2. Team Crocodile's eco-car uses 1.3 kWh per 100 km. Photo kindly provided by Team Crocodile. `www.teamcrocodile.com`

How to roll better

A widely quoted statistic says something along the lines of "only *1 percent* of the energy used by a car goes into moving the driver" – the implication being that, surely, by being a bit smarter, we could make cars *100* times more efficient? The answer is yes, almost, but only by applying the principles of vehicle design and vehicle use, listed above, to *extreme* degrees.

One illustration of extreme vehicle design is an eco-car, which has small frontal area and low weight, and – if any records are to be broken – is carefully driven at a low and steady speed. The *Team Crocodile* eco-car (figure 20.2) does 2184 miles per gallon (1.3 kWh per 100 km) at a speed of 15 mph (24 km/h). Weighing 50 kg and shorter in height than a traffic cone, it comfortably accommodates one teenage driver.

Figure 20.3. "Babies on board." This mode of transportation has an energy cost of 1 kWh per 100 person-km.

Hmm. I think that the driver of the urban tractor in figure 20.1 might detect a change in "look, feel and performance" if we switched them to the eco-car and instructed them to keep their speed below 15 miles per hour. So, the idea that cars could easily be 100 times more energy efficient is a myth. We'll come back to the challenge of making energy-efficient cars in a moment. But first, let's see some other ways of satisfying the principles of more-efficient surface transport.

Figure 20.3 shows a multi-passenger vehicle that is at least 25 times more energy-efficient than a standard petrol car: a bicycle. The bicycle's performance (in terms of energy per distance) is about the same as the eco-car's. Its speed is the same, its mass is lower than the eco-car's (because the human replaces the fuel tank and engine), and its effective frontal area is higher, because the cyclist is not so well streamlined as the eco-car.

Figure 20.4. This 8-carriage train, at its maximum speed of 100 mph (161 km/h), consumes 1.6 kWh per 100 passenger-km, if full.

Figure 20.4 shows another possible replacement for the petrol car: a train, with an energy-cost, if full, of 1.6 kWh per 100 passenger-km. In contrast to the eco-car and the bicycle, trains manage to achieve outstanding efficiency without travelling slowly, and without having a low weight per person. Trains make up for their high speed and heavy frame by exploiting the principle of small frontal area per person. Whereas a cyclist

and a regular car have effective frontal areas of about 0.8 m^2 and 0.5 m^2 respectively, a full commuter train from Cambridge to London has a frontal area per passenger of 0.02 m^2.

But whoops, now we've broached an ugly topic – the prospect of sharing a vehicle with "all those horrible people." Well, squish aboard, and let's ask: How much could consumption be reduced by a switch from personal gas-guzzlers to excellent integrated public transport?

4.4 kWh per 100 p-km, if full

3–9 kWh per 100 seat-km, if full

Figure 20.5. Some public transports, and their energy-efficiencies, when on best behaviour.
Tubes, outer and inner.
Two high-speed trains. The electric one uses 3 kWh per 100 seat-km; the diesel, 9 kWh.
Trolleybuses in San Francisco.
Vancouver SeaBus. Photo by Larry.

7 kWh per 100 p-km, if full

21 kWh per 100 p-km, if full

Public transport

At its best, shared public transport is far more energy-efficient than individual car-driving. A diesel-powered **coach**, carrying 49 passengers and doing 10 miles per gallon at 65 miles per hour, uses 6 kWh per 100 p-km – 13 times better than the single-person car. Vancouver's **trolleybuses** consume 270 kWh per vehicle-km, and have an average speed of 15 km/h. If the trolleybus has 40 passengers on board, then its passenger transport cost is 7 kWh per 100 p-km. The Vancouver **SeaBus** has a transport cost of 83 kWh per vehicle-km at a speed of 13.5 km/h. It can seat 400 people, so its passenger transport cost when full is 21 kWh per 100 p-km. London **underground trains**, at peak times, use 4.4 kWh per 100 p-km – 18 times better than individual cars. Even **high-speed trains**, which violate two of our energy-saving principles by going twice as fast as the car and weighing a lot, are much more energy efficient: if the electric high-speed train

is full, its energy cost is 3 kWh per 100 p-km – that's 27 times smaller than the car's!

However, we must be realistic in our planning. Some trains, coaches, and buses are not full (figure 20.6). So the *average* energy cost of public transport is bigger than the best-case figures just mentioned. What's the *average* energy-consumption of public transport systems, and what's a realistic appraisal of how good they could be?

Figure 20.6. Some trains aren't full. Three men and a cello – the sole occupants of this carriage of the 10.30 high-speed train from Edinburgh to Kings Cross.

In 2006–7, the total energy cost of all London's underground trains, including lighting, lifts, depots, and workshops, was 15 kWh per 100 p-km – five times better than our baseline car. In 2006–7 the energy cost of all London buses was 32 kWh per 100 p-km. Energy cost is not the only thing that matters, of course. Passengers care about speed: and the underground trains delivered higher speeds (an average of 33 km/h) than buses (18 km/h). Managers care about financial costs: the staff costs, per passenger-km, of underground trains are less than those of buses.

32 kWh per 100 p-km

9 kWh per 100 p-km

Figure 20.7. Some public transports, and their *average* energy consumptions. Left: Some red buses. Right: Croydon Tramlink. Photo by Stephen Parascandolo.

The total energy consumption of the Croydon Tramlink system (figure 20.7) in 2006–7 (including the tram depot and facilities at tram-stops) was 9 kWh per 100 p-km, with an average speed of 25 km/h.

How good could public transport be? Perhaps we can get a rough indication by looking at the data from Japan in table 20.8. At 19 kWh per 100 p-km and 6 kWh per 100 p-km, bus and rail both look promising. Rail has the nice advantage that it can solve both of our goals – reduction in energy consumption, and independence from fossil fuels. Buses and coaches have obvious advantages of simplicity and flexibility, but keeping this flexibility at the same time as getting buses and coaches to work without fossil fuels may be a challenge.

Energy consumption (kWh per 100 p-km)	
Car	68
Bus	19
Rail	6
Air	51
Sea	57

Table 20.8. Overall transport efficiencies of transport modes in Japan (1999).

To summarise, public transport (especially electric trains, trams, and buses) seems a promising way to deliver passenger transportation – better in terms of energy per passenger-km, perhaps five or ten times better than cars. However, if people demand the flexibility of a private vehicle, what are our other options?

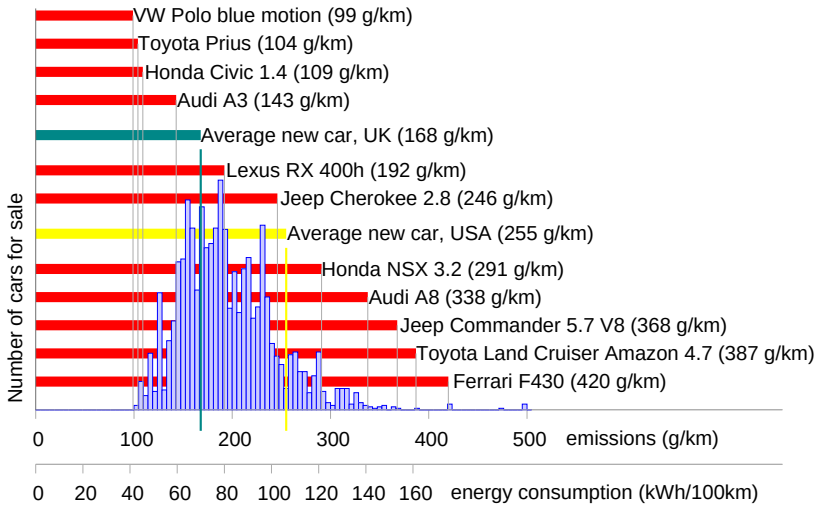


Figure 20.9. Carbon pollution, in grams CO_2 per km, of a selection of cars for sale in the UK. The horizontal axis shows the emission rate, and the height of the blue histogram indicates the number of models on sale with those emissions in 2006. Source: `www.newcarnet.co.uk`.
The second horizontal scale indicates approximate energy consumptions, assuming that 240 g CO_2 is associated with 1 kWh of chemical energy.

Private vehicles: technology, legislation, and incentives

The energy consumption of individual cars *can* be reduced. The wide range of energy efficiencies of cars for sale proves this. In a single showroom in 2006 you could buy a Honda Civic 1.4 that uses roughly 44 kWh per 100 km, or a Honda NSX 3.2 that uses 116 kWh per 100 km (figure 20.9). The fact that people merrily *buy* from this wide range is also proof that we need extra incentives and legislation to encourage the blithe consumer to *choose* more energy-efficient cars. There are various ways to help consumers prefer the Honda Civic over the Honda NSX 3.2 gas-guzzler: raising the price of fuel; cranking up the showroom tax (the tax on new cars) in proportion to the predicted lifetime consumption of the vehicle; cranking up the road-tax on gas guzzlers; parking privileges for economical cars (figure 20.10); or fuel rationing. All such measures are unpopular with at least some voters. Perhaps a better legislative tactic would be to *enforce* reasonable energy-efficiency, rather than continuing to allow unconstrained choice; for example, we could simply *ban*, from a certain date, the sale of *any* car whose energy consumption is more than 80 kWh per 100 km; and then, over time, reduce this ceiling to 60 kWh per 100 km, then 40 kWh per 100 km, and beyond. Alternatively, to give the consumer more choice, regulations could force car manufacturers to reduce the *average* energy consumption of all the cars they sell. Additional legislation limiting the weight and frontal area of vehicles would simultaneously reduce fuel consumption and improve safety for other road-users (figure 20.11). People today choose their cars to make fashion statements. With strong efficiency legislation, there could still be a wide choice of fashions; they'd all just happen to be energy-efficient. You could choose any colour, as long as it was green.

Figure 20.10. Special parking privileges for electric cars in Ann Arbor, Michigan.

Figure 20.11. Monstercars are just tall enough to completely obscure the view and the visibility of pedestrians.

While we wait for the voters and politicians to agree to legislate for efficient cars, what other options are available?

Figure 20.12. A roundabout in Enschede, Netherlands.

Bikes

My favourite suggestion is the provision of excellent cycle facilities, along with appropriate legislation (lower speed-limits, and collision regulations that favour cyclists, for example). Figure 20.12 shows a roundabout in Enschede, Netherlands. There are two circles: the one for cars lies inside the one for bikes, with a comfortable car's length separating the two. The priority rules are the same as those of a British roundabout, except that cars exiting the central circle must give way to circulating cyclists (just as British cars give way to pedestrians on zebra crossings). Where excellent cycling facilities are provided, people will use them, as evidenced by the infinite number of cycles sitting outside the Enschede railway station (figure 20.13).

Figure 20.13. A few Dutch bikes.

Somehow, British cycle provision (figure 20.14) doesn't live up to the Dutch standard.

Figure 20.14. Meanwhile, back in Britain...
Photo on right by Mike Armstrong.

In the French city of Lyon, a privately-run public bicycle network, Vélo'v, was introduced in 2005 and has proved popular. Lyon's population of 470 000 inhabitants is served by 2000 bikes distributed around 175 cycle-stations in an area of 50 km^2 (figure 20.15). In the city centre, you're usually within 400 metres of a cycle-station. Users join the scheme by paying a subscription fee of €10 per year and may then hire bicycles free for all trips lasting less than 30 minutes. For longer hire periods, users pay up to €1 per hour. Short-term visitors to Lyon can buy one-week subscriptions for €1.

Figure 20.15. A Vélo'v station in Lyon.

Other legislative opportunities

Speed limits are a simple knob that could be twiddled. As a rule, cars that travel slower use less energy (see Chapter A). With practice, drivers can learn to drive more economically: using the accelerator and brake less and always driving in the highest possible gear can give a 20% reduction in fuel consumption.

Another way to reduce fuel consumption is to reduce congestion. Stopping and starting, speeding up and slowing down, is a much less efficient way to get around than driving smoothly. Idling in stationary traffic is an especially poor deliverer of miles per gallon!

Congestion occurs when there are too many vehicles on the roads. So one simple way to reduce congestion is to group travellers into fewer vehicles. A striking way to think about a switch from cars to coaches is to calculate the road area required by the two modes. Take a trunk road on the verge of congestion, where the desired speed is 60 mph. The safe distance from one car to the next at 60 mph is 77 m. If we assume there's one car every 80 m and that each car contains 1.6 people, then vacuuming up 40 people into a single coach frees up *two kilometres* of road!

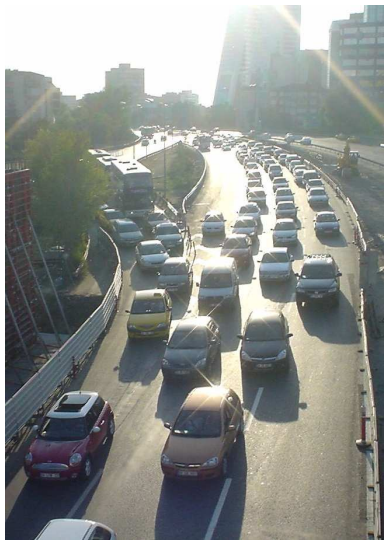


Figure 20.16. With congestion like this, it's faster to walk.

Congestion can be reduced by providing good alternatives (cycle lanes, public transport), and by charging road users extra if they contribute to congestion. In this chapter's notes I describe a fair and simple method for handling congestion-charging.

Enhancing cars

Assuming that the developed world's love-affair with the car is not about to be broken off, what are the technologies that can deliver significant energy savings? Savings of 10% or 20% are easy – we've already discussed some ways to achieve them, such as making cars smaller and lighter. Another option is to switch from petrol to diesel. Diesel engines are more expensive to make, but they tend to be more fuel-efficient. But are there technologies that can radically increase the efficiency of the energy-conversion chain? (Recall that in a standard petrol car, 75% of the energy is turned

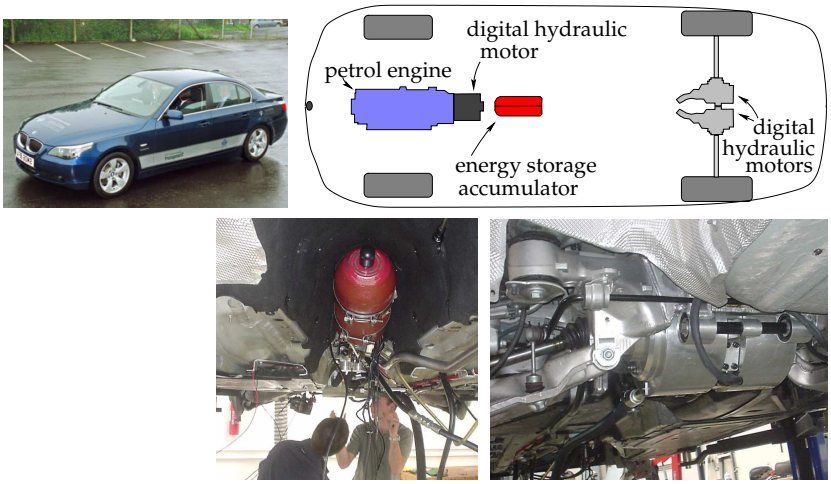


Figure 20.17. A BMW 530i modified by Artemis Intelligent Power to use digital hydraulics. Lower left: A 6-litre accumulator (the red canister), capable of storing about 0.05 kWh of energy in compressed nitrogen. Lower right: Two 200 kW hydraulic motors, one for each rear wheel, which both accelerate and decelerate the car. The car is still powered by its standard 190 kW petrol engine, but thanks to the digital hydraulic transmission and regenerative braking, it uses 30% less fuel.

into heat and blown out of the radiator!) And what about the goal of getting off fossil fuels?

In this section, we'll discuss five technologies: regenerative braking; hybrid cars; electric cars; hydrogen-powered cars; and compressed-air cars.

Regenerative braking

There are four ways to capture energy as a vehicle slows down.

1. An electric generator coupled to the wheels can charge up an electric battery or supercapacitor.
2. Hydraulic motors driven by the wheels can make compressed air, stored in a small canister.
3. Energy can be stored in a flywheel.
4. Braking energy can be stored as gravitational energy by driving the vehicle up a ramp whenever you want to slow down. This gravitational energy storage option is rather inflexible, since there must be a ramp in the right place. It's an option that's most useful for trains, and it is illustrated by the London Underground's Victoria line, which has hump-back stations. Each station is at the top of a hill in the track. Arriving trains are automatically slowed down by the hill, and departing trains are accelerated as they go down the far side of the hill. The hump-back-station design provides an energy saving of 5% and makes the trains run 9% faster.

Electric regenerative braking (using a battery to store the energy) salvages roughly 50% of the car's energy in a braking event, leading to perhaps a 20% reduction in the energy cost of city driving.

Regenerative systems using flywheels and hydraulics seem to work a little better than battery-based systems, salvaging at least 70% of the braking energy. Figure 20.17 describes a hybrid car with a petrol engine powering digitally-controlled hydraulics. On a standard driving cycle, this car uses 30% less fuel than the original petrol car. In urban driving, its energy consumption is halved, from 131 kWh per 100 km to 62 kWh per 100 km (20 mpg to 43 mpg). (Credit for this performance improvement must be shared between regenerative braking and the use of hybrid technology.) Hydraulics and flywheels are both promising ways to handle regenerative braking because small systems can handle large powers. A flywheel system weighing just 24 kg (figure 20.18), designed for energy storage in a racing car, can store 400 kJ (0.1 kWh) of energy – enough energy to accelerate an ordinary car up to 60 miles per hour (97 km/h); and it can accept or deliver 60 kW of power. Electric batteries capable of delivering that much power would weigh about 200 kg. So, unless you're already carrying that much battery on board, an electrical regenerative-braking system should probably use capacitors to store braking energy. Super-capacitors have similar energy-storage and power-delivery parameters to the flywheel's.

Figure 20.18. A flywheel regenerative-braking system. Photos courtesy of Flybrid Systems.

Hybrid cars

Hybrid cars such as the Toyota Prius (figure 20.19) have more-efficient engines and electric regenerative braking, but to be honest, today's hybrid vehicles don't really stand out from the crowd (figure 20.9).

Figure 20.19. Toyota Prius – according to Jeremy Clarkson, "a very expensive, very complex, not terribly green, slow, cheaply made, and pointless way of moving around."

The horizontal bars in figure 20.9 highlight a few cars including two hybrids. Whereas the average new car in the UK emits 168 g, the hybrid Prius emits about 100 g of CO_2 per km, as do several other non-hybrid vehicles – the VW Polo blue motion emits 99 g/km, and there's a Smart car that emits 88 g/km.

The Lexus RX 400h is the second hybrid, advertised with the slogan "LOW POLLUTION. ZERO GUILT." But its CO_2 emissions are 192 g/km – worse than the average UK car! The advertising standards authority ruled that this advertisement breached the advertising codes on Truthfulness, Comparisons and Environmental claims. "We considered that ... readers were likely to understand that the car caused little or no harm to the environment, which was not the case, and had low emissions in comparison with all cars, which was also not the case."

In practice, hybrid technologies seem to give fuel savings of 20 or 30%. So neither these petrol/electric hybrids, nor the petrol/hydraulic hybrid featured in figure 20.17 seems to me to have really cracked the transport challenge. A 30% reduction in fossil-fuel consumption is impressive, but it's not enough by this book's standards. Our opening assumption was that we want to get off fossil fuels, or at least to reduce fossil fuel use by 90%. Can this goal be achieved without reverting to bicycles?

Figure 20.20. Electric vehicles. From left to right: the G-Wiz; the rotting corpse of a Sinclair C5; a Citroën Berlingo; and an Elettrica.

Electric vehicles

The REVA electric car was launched in June 2001 in Bangalore and is exported to the UK as the G-Wiz. The G-Wiz's electric motor has a peak power of 13 kW, and can produce a sustained power of 4.8 kW. The motor provides regenerative braking. It is powered by eight 6-volt lead acid batteries, which when fully charged give a range of "up to 77 km." A full charge consumes 9.7 kWh of electricity. These figures imply a transport cost of 13 kWh per 100 km.

Manufacturers always quote the best possible performance of their products. What happens in real life? The real-life performance of a G-Wiz in London is shown in figure 20.21. Over the course of 19 recharges, the average transport cost of this G-Wiz is 21 kWh per 100 km – about four times better than an average fossil fuel car. The best result was 16 kWh per 100 km, and the worst was 33 kWh per 100 km. If you are interested in carbon emissions, 21 kWh per 100 km is equivalent to 105 g CO_2 per km, assuming that electricity has a footprint of 500 g CO_2 per kWh.

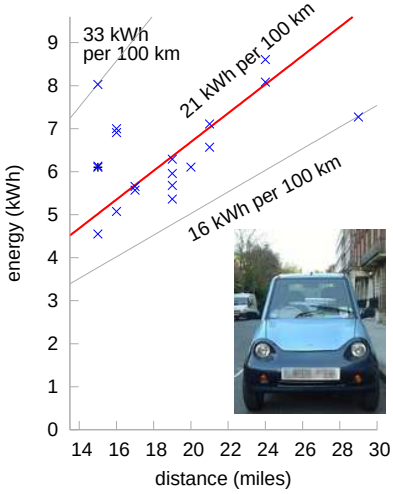


Figure 20.21. Electricity required to recharge a G-Wiz versus distance driven. Measurements were made at the socket.

Now, the G-Wiz sits at one end of the performance spectrum. What if we demand more – more acceleration, more speed, and more range? At the other end of the spectrum is the Tesla Roadster. The Tesla Roadster 2008 has a range of 220 miles (354 km); its lithium-ion battery pack stores 53 kWh and weighs 450 kg (120 Wh/kg). The vehicle weighs 1220 kg and its motor's maximum power is 185 kW. What is the energy-consumption of this muscle car? Remarkably, it's better than the G-Wiz: 15 kWh per 100 km. Evidence that a range of 354 km should be enough for most people most of the time comes from the fact that only 8.3% of commuters travel more than 30 km to their workplace.

Figure 20.22. Tesla Roadster: 15 kWh per 100 km. `www.teslamotors.com`.

I've looked up the performance figures for lots of electric vehicles – they're listed in this chapter's end-notes – and they seem to be consistent with this summary: electric vehicles can deliver transport at an energy cost of roughly 15 kWh per 100 km. That's five times better than our baseline fossil-car, and significantly better than any hybrid cars. Hurray! To achieve economical transport, we don't have to huddle together in public transport – we can still hurtle around, enjoying all the pleasures and freedoms of solo travel, thanks to electric vehicles.

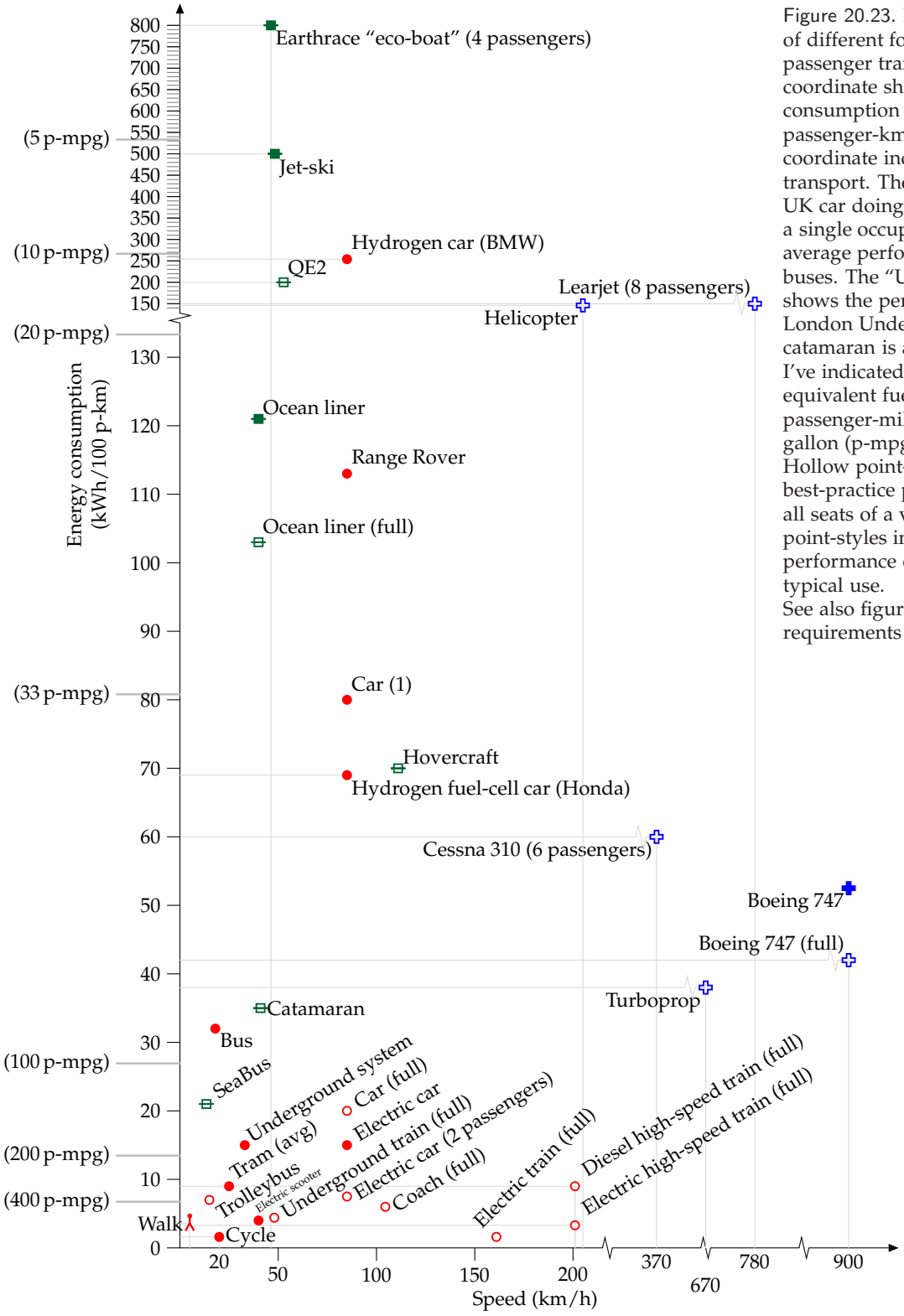


Figure 20.23. Energy requirements of different forms of passenger transport. The vertical coordinate shows the energy consumption in kWh per 100 passenger-km. The horizontal coordinate indicates the speed of the transport. The "Car (1)" is an average UK car doing 33 miles per gallon with a single occupant. The "Bus" is the average performance of all London buses. The "Underground system" shows the performance of the whole London Underground system. The catamaran is a diesel-powered vessel. I've indicated on the left-hand side equivalent fuel efficiencies in passenger-miles per imperial gallon (p-mpg).
Hollow point-styles show best-practice performance, assuming all seats of a vehicle are in use. Filled point-styles indicate actual performance of a vehicle in typical use.
See also figure 15.8 (energy requirements of freight transport).

This moment of celebration feels like a good time to unveil this chapter's big summary diagram, figure 20.23, which shows the energy requirements of all the forms of passenger-transport we have discussed and a couple that are still to come.

OK, the race is over, and I've announced two winners – public transport, and electric vehicles. But are there any other options crossing the finishing line? We have yet to hear about the compressed-air-powered car and the hydrogen car. If either of these turns out to be better than electric car, it won't affect the long-term picture very much: whichever of these three technologies we went for, the vehicles would be charged up using energy generated from a "green" source.

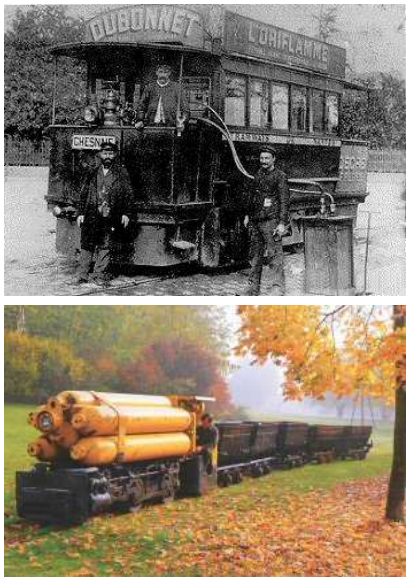


Figure 20.24. Top: A compressed-air tram taking on air and steam in Nantes. Powering the trams of Nantes used 4.4 kg of coal (36 kWh) per vehicle-km, or 115 kWh per 100 p-km, if the trams were full. [5qhvcb] Bottom: A compressed-air locomotive; weight 9.2 t, pressure 175 bar, power 26 kW; photo courtesy of Rüdiger Fach, Rolf-Dieter Reichert, and Frankfurter Feldbahnmuseum.

Compressed-air cars

Air-powered vehicles are not a new idea. Hundreds of trams powered by compressed air and hot water plied the streets of Nantes and Paris from 1879 to 1911. Figure 20.24 shows a German pneumatic locomotive from 1958. I think that in terms of energy efficiency the compressed-air technique for storing energy isn't as good as electric batteries. The problem is that compressing the air generates *heat* that's unlikely to be used efficiently; and expanding the air generates *cold*, another by-product that is unlikely to be used efficiently. But compressed air may be a superior technology to electric batteries in other ways. For example, air can be compressed thousands of times and doesn't wear out! It's interesting to note, however, that the first product sold by the Aircar company is actually an *electric* scooter. [www.theaircar.com/acf]

There's talk of Tata Motors in India manufacturing air-cars, but it's hard to be sure whether the compressed-air vehicle is going to see a revival, because no-one has published the specifications of any modern prototypes. Here's the fundamental limitation: the energy-density of compressed-air energy-stores is only about 11–28 Wh per kg, which is similar to lead-acid batteries, and roughly five times smaller than lithium-ion batteries. (See figure 26.13, p199, for details of other storage technologies.) So the range of a compressed-air car will only ever be as good as the range of the earliest electric cars. Compressed-air storage systems do have three advantages over batteries: longer life, cheaper construction, and fewer nasty chemicals.

Figure 20.25. The Hummer H2H: embracing the green revolution, the American way. Photo courtesy of General Motors.

Hydrogen cars – blimp your ride

I think hydrogen is a hyped-up bandwagon. I'll be delighted to be proved wrong, but I don't see how hydrogen is going to help us with our energy problems. Hydrogen is not a miraculous *source* of energy; it's just an energy *carrier*, like a rechargeable battery. And it is a rather inefficient energy carrier, with a whole bunch of practical defects.

The "hydrogen economy" received support from *Nature* magazine in

a column praising California Governor Arnold Schwarzenegger for filling up a hydrogen-powered Hummer (figure 20.25). Nature's article lauded Arnold's vision of hydrogen-powered cars replacing "polluting models" with the quote "the governor is a real-life climate action hero." But the critical question that needs to be asked when such hydrogen heroism is on display is "where is the *energy* to come from to *make* the hydrogen?" Moreover, converting energy to and from hydrogen can only be done inefficiently – at least, with today's technology.

Here are some numbers.

- In the CUTE (Clean Urban Transport for Europe) project, which was intended to demonstrate the feasibility and reliability of fuel-cell buses and hydrogen technology, fuelling the hydrogen buses required between 80% and 200% *more* energy than the baseline diesel bus.
- Fuelling the *Hydrogen 7*, the hydrogen-powered car made by BMW, requires 254 kWh per 100 km – *220% more* energy than an average European car.

Figure 20.26. BMW Hydrogen 7. Energy consumption: 254 kWh per 100 km. Photo from BMW.

If our task were "please stop using fossil fuels for transport, allowing yourself the assumption that *infinite* quantities of green electricity are available for free," then of course an energy-profligate transport solution like hydrogen might be a contender (though hydrogen faces other problems). But *green electricity is not free*. Indeed, getting green electricity on the scale of our current consumption is going to be very challenging. The fossil fuel challenge is an energy challenge. The climate-change problem is an energy problem. We need to focus on solutions that use less energy, not "solutions" that use more! *I know of no form of land transport whose energy consumption is worse than this hydrogen car*. (The only transport methods I know that are worse are jet-skis – using about 500 kWh per 100 km – and the *Earthrace* biodiesel-powered speed-boat, absurdly called an eco-boat, which uses 800 kWh per 100 p-km.)

Figure 20.27. The Earthrace "eco-boat." Photo by David Castor.

Hydrogen advocates may say "the BMW Hydrogen 7 is just an early prototype, and it's a luxury car with lots of muscle – the technology is going to get more efficient." Well, I hope so, because it has a lot of catching up to do. The Tesla Roadster (figure 20.22) is an early prototype too, and it's also a luxury car with lots of muscle. And it's more than ten times more energy-efficient than the Hydrogen 7! Feel free to put your money on the hydrogen horse if you want, and if it wins in the end, fine. But it seems daft to back the horse that's so far behind in the race. Just look at figure 20.23 – if I hadn't squished the top of the vertical axis, the hydrogen car would not have fitted on the page!

Figure 20.28. The Honda FCX Clarity hydrogen-powered fuel-cell sedan, with a Jamie Lee Curtis for scale. Photo courtesy of `automobiles.honda.com`.

Yes, the Honda fuel-cell car, the FCX Clarity, does better – it rolls in at 69 kWh per 100 km – but my prediction is that after all the "zero-emissions" trumpeting is over, we'll find that hydrogen cars use just as much energy as the average fossil car of today.

Here are some other problems with hydrogen. Hydrogen is a less convenient energy storage medium than most liquid fuels, because of its bulk, whether stored as a high pressure gas or as a liquid (which requires a temperature of −253 °C). Even at a pressure of 700 bar (which requires a hefty pressure vessel) its energy density (energy per unit volume) is 22% of gasoline's. The cryogenic tank of the BMW Hydrogen 7 weighs 120 kg and stores 8 kg of hydrogen. Furthermore, hydrogen gradually leaks out of any practical container. If you park your hydrogen car at the railway station with a full tank and come back a week later, you should expect to find most of the hydrogen has gone.

Some questions about electric vehicles

You've shown that electric cars are more energy-efficient than fossil cars. But are they better if our objective is to reduce CO_2 emissions, and the electricity is still generated by fossil power-stations?

This is quite an easy calculation to do. Assume the electric vehicle's energy cost is 20 kWh(e) per 100 km. (I think 15 kWh(e) per 100 km is perfectly possible, but let's play sceptical in this calculation.) If grid electricity has a carbon footprint of 500 g per kWh(e) then the effective emissions of this vehicle are **100 g CO_2 per km**, which is as good as the best fossil cars (figure 20.9). So I conclude that switching to electric cars is *already* a good idea, even before we green our electricity supply.

Electric cars, like fossil cars, have costs of both manufacture and use. Electric cars may cost less to use, but if the batteries don't last very long, shouldn't you pay more attention to the manufacturing cost?

Yes, that's a good point. My transport diagram shows only the use cost. If electric cars require new batteries every few years, my numbers may be underestimates. The batteries in a Prius are expected to last just 10 years, and a new set would cost £3500. Will anyone want to own a 10-year old Prius and pay that cost? It could be predicted that most Priuses will be junked at age 10 years. This is certainly a concern for all electric vehicles that have batteries. I guess I'm optimistic that, as we switch to electric vehicles, battery technology is going to improve.

I live in a hot place. How could I drive an electric car? I demand power-hungry air-conditioning!

There's an elegant fix for this demand: fit 4 m^2 of photovoltaic panels in the upward-facing surfaces of the electric car. If the air-conditioning is needed, the sun must surely be shining. 20%-efficient panels will generate up to 800 W, which is enough to power a car's air-conditioning. The panels might even make a useful contribution to charging the car when it's parked, too. Solar-powered vehicle cooling was included in a Mazda in 1993; the solar cells were embedded in the glass sunroof.

I live in a cold place. How could I drive an electric car? I demand power-hungry heating!

The motor of an electric vehicle, when it's running, will on average use something like 10 kW, with an efficiency of 90–95%. Some of the lost power, the other 5–10%, will be dissipated as heat in the motor. Perhaps electric cars that are going to be used in cold places can be carefully designed so that this motor-generated heat, which might amount to 250 or 500 W, can be piped from the motor into the car. That much power would provide some significant windscreen demisting or body-warming.

Are lithium-ion batteries safe in an accident?

Some lithium-ion batteries are unsafe when short-circuited or overheated, but the battery industry is now producing safer batteries such as lithium phosphate. There's a fun safety video at `www.valence.com`.

Is there enough lithium to make all the batteries for a huge fleet of electric cars?

World lithium reserves are estimated to be 9.5 million tons in ore deposits (p175). A lithium-ion battery is 3% lithium. If we assume each vehicle has a 200 kg battery, then we need 6 kg of lithium per vehicle. So the estimated reserves in ore deposits are enough to make the batteries for 1.6 billion vehicles. That's more than the number of cars in the world today (roughly 1 billion) – but not much more, so the amount of lithium may be a concern, especially when we take into account the competing ambitions of the nuclear fusion posse (Chapter 24) to guzzle lithium in their reactors. There's many thousands times more lithium in sea water, so perhaps the oceans will provide a useful backup. However, lithium specialist R. Keith Evans says "concerns regarding lithium availability for hybrid or electric vehicle batteries or other foreseeable applications are unfounded." And anyway, other lithium-free battery technologies such as zinc-air rechargeables are being developed [`www.revolttechnology.com`]. I think the electric car is a goer!

The future of flying?

The superjumbo A380 is said by Airbus to be "a highly fuel-efficient aircraft." In fact, it burns just 12% less fuel per passenger than a 747.

Boeing has announced similar breakthroughs: their new 747–8 Intercontinental, trumpeted for its planet-saving properties, is (according to Boeing's advertisements) only 15% more fuel-efficient than a 747–400.

This slender rate of progress (contrasted with cars, where changes in technology deliver two-fold or even ten-fold improvements in efficiency) is explained in Technical Chapter C. Planes are up against a fundamental limit imposed by the laws of physics. Any plane, whatever its size, *has to* expend an energy of about 0.4 kWh per ton-km on keeping up and keeping

Figure 20.29. Airbus A380.

moving. Planes have already been fantastically optimized, and there is no prospect of significant improvements in plane efficiency.

For a time, I thought that the way to solve the long-distance-transport problem was to revert to the way it was done before planes: ocean liners. Then I looked at the numbers. The sad truth is that ocean liners use more energy per passenger-km than jumbo jets. The QE2 uses four times as much energy per passenger-km as a jumbo. OK, it's a luxury vessel; can we do better with slower tourist-class liners? From 1952 to 1968, the economical way to cross the Atlantic was in two Dutch-built liners known as "The Economy Twins," the Maasdam and the Rijnsdam. These travelled at 16.5 knots (30.5 km/h), so the crossing from Britain to New York took eight days. Their energy consumption, if they carried a full load of 893 passengers, was 103 kWh per 100 p-km. At a typical 85% occupancy, the energy consumption was 121 kWh per 100 pkm – more than twice that of the jumbo jet. To be fair to the boats, they are not only providing transportation: they also provide the passengers and crew with hot air, hot water, light, and entertainment for several days; but the energy saved back home from being cooped up on the boat is dwarfed by the boat's energy consumption, which, in the case of the QE2, is about 3000 kWh per day per passenger.

So, sadly, I don't think boats are going to beat planes in energy consumption. If eventually we want a way of travelling large distances without fossil fuels, perhaps nuclear-powered ships are an interesting option (figures 20.31 & 20.32).

Figure 20.30. TSS Rijndam.

Figure 20.31. NS Savannah, the first commercial nuclear-powered cargo vessel, passing under the Golden Gate Bridge in 1962.

What about freight?

International shipping is a surprisingly efficient user of fossil fuels; so getting road transport off fossil fuels is a higher priority than getting ships off fossil fuels. But fossil fuels are a finite resource, and eventually ships must be powered by something else. Biofuels *may* work out. Another option will be nuclear power. The first nuclear-powered ship for carrying cargo and passengers was the NS Savannah, launched in 1962 as part of President Dwight D. Eisenhower's *Atoms for Peace* initiative (figure 20.31). Powered by one 74-MW nuclear reactor driving a 15-MW motor, the Savannah had a service speed of 21 knots (39 km/h) and could carry 60 passengers and 14 000 t of cargo. That's a cargo transport cost of 0.14 kWh per ton-km. She could travel 500 000 km without refuelling. There are already many nuclear-powered ships, both military and civilian. Russia has ten nuclear-powered ice-breakers, for example, of which seven are still active. Figure 20.32 shows the nuclear ice-breaker Yamal, which has two 171-MW reactors, and motors that can deliver 55 MW.

Figure 20.32. The nuclear ice-breaker Yamal, carrying 100 tourists to the North Pole in 2001. Photo by Wofratz.

"Hang on! You haven't mentioned magnetic levitation"

The German company, Transrapid, which made the maglev train for Shanghai, China (figure 20.33), says: "The Transrapid Superspeed Maglev System is unrivaled when it comes to noise emission, energy consumption, and land use. The innovative non-contact transportation system provides mobility without the environment falling by the wayside."

Magnetic levitation is one of many technologies that gets hyped up when people are discussing energy issues. In energy-consumption terms, the comparison with other fast trains is actually not as flattering as the hype suggests. The Transrapid site compares the Transrapid with the InterCityExpress (ICE), a high-speed electric train.

Fast trains compared at 200 km/h (125mph)	
Transrapid	2.2 kWh per 100 seat-km
ICE	2.9 kWh per 100 seat-km

The main reasons why maglev is slightly better than the ICE are: the magnetic propulsion motor has high efficiency; the train itself has low mass, because most of the propulsion system is in the track, rather than the train; and more passengers are inside the train because space is not needed for motors. Oh, and perhaps because the data are from the maglev company's website, so are bound to make the maglev look better!

Incidentally, people who have seen the Transrapid train in Shanghai tell me that at full speed it is "about as quiet as a jet aircraft."

Figure 20.33. A maglev train at Pudong International Airport, Shanghai.

"driving without wheels; flying without wings."

Photo by Alex Needham.

Figure 20.34. Nine out of ten vehicles in London are G-Wizes. (And 95% of statistics are made up.)

Notes and further reading

page no.

119 *A widely quoted statistic says "Only 1% of fuel energy in a car goes into moving the driver."* In fact the percentage in this myth varies in size as it commutes around the urban community. Some people say "5% of the energy goes into moving the driver." Others say "A mere *three tenths of 1 percent* of fuel energy goes into moving the driver." [4qgg8q] My take, by the way, is that none of these statistics is correct or helpful.

– *The bicycle's performance is about the same as the eco-car's.* Cycling on a single-person bike costs about 1.6 kWh per 100 km, assuming a speed of 20 km/h. For details and references, see Chapter A, p262.

– *The 8-carriage stopping train from Cambridge to London* (figure 20.4) weighs 275 tonnes, and can carry 584 passengers seated. Its maximum speed is 100 mph (161 km/h), and the power output is 1.5 MW. If all the seats are occupied, this train at top speed consumes at most 1.6 kWh per 100 passenger-km.

120 *London Underground.* A Victoria-line train consists of four 30.5-ton and four 20.5-ton cars (the former carrying the motors). Laden, an average train weighs 228 tons. The maximum speed is 45 mile/h. The average speed is 31 mph. A train with most seats occupied carries about 350 passengers; crush-loaded, the train takes about 620. The energy consumption at peak times is about 4.4 kWh per 100 passenger-km (Catling, 1966).

121 *High-speed train.*
A diesel-powered intercity 125 train (on the right in figure 20.5) weighs 410 tons. When travelling at 125 mph, the power delivered "at the rail" is 2.6 MW. The number of passengers in a full train is about 500. The average fuel consumption is about 0.84 litres of diesel per 100 seat-km [5o5x5m], which is a transport cost of about 9 kWh per 100 seat-km. The Class 91 electric train (on the left in figure 20.5) travels at 140 mph (225 km/h) and uses 4.5 MW. According to Roger Kemp, this train's average energy consumption is 3 kWh per 100 seat-km [5o5x5m]. The government document [5fbeg9] says that east-coast mainline and west-coast mainline trains both consume about 15 kWh per km (whole train). The number of seats in each train is 526 or 470 respectively. So that's 2.9–3.2 kWh per 100 seat-km.

– *the total energy cost of all London's underground trains, was 15 kWh per 100 p-km. … The energy cost of all London buses was 32 kWh per 100 p-km.* Source: [679rpc]. Source for train speeds and bus speeds: Ridley and Catling (1982).

– *Croydon Tramlink.*
www.tfl.gov.uk/assets/downloads/corporate/TfL-environment-report-2007.pdf, www.tfl.gov.uk/assets/downloads/corporate/London-Travel-Report-2007-final.pdf, www.croydon-tramlink.co.uk.

123 *… provision of excellent cycle facilities …* The UK street design guide [www.manualforstreets.org.uk] encourages designing streets to make 20 miles per hour the natural speed. See also Franklin (2007).

124 *A fair and simple method for handling congestion-charging.* I learnt a brilliant way to automate congestion-charging from Stephen Salter. A simple daily congestion charge, as levied in London, sends only a crude signal to drivers; once a car-owner has decided to pay the day's charge and drive into a congestion zone, he has no incentive to drive *little* in the zone. Nor is he rewarded with any rebate if he carefully chooses routes in the zone that are not congested.
Instead of having a centralized authority that decides in advance when and where the congestion-charge zones are, with expensive and intrusive monitoring and recording of vehicle movements into and within all those zones, Salter has a simpler, decentralized, anonymous method of charging drivers for driving in heavy, slow traffic, wherever and whenever it actually exists. The system would operate nationwide. Here's how it works. We want a device that answers the question "how congested is the traffic I am driving in?" A good measure of congestion is "how many other active vehicles are close to mine?" In fast-moving traffic, the spacing between vehicles is larger than slow-moving traffic. Traffic that's trundling in tedious queues is the

Figure 20.35. 100 km in a single-person car, compared with 100 km on a fully-occupied electric high-speed train.

Figure 20.36. Trams work nicely in Istanbul and Prague too.

most densely packed. The number of nearby vehicles that are active can be sensed anonymously by fitting in every vehicle a radio transmitter/receiver (like a very cheap mobile phone) that transmits little radio-bleeps at a steady rate whenever the engine is running, and that counts the number of bleeps it hears from other vehicles. The congestion charge would be proportional to the number of bleeps received; this charge could be paid at refuelling stations whenever the vehicle is refuelled. The radio transmitter/receiver would replace the current UK road tax disc.

126 *hydraulics and flywheels salvage at least 70% of the braking energy.* Compressed air is used for regenerative braking in trucks; `eaton.com` say "hydraulic launch assist" captures 70% of the kinetic energy. [`5cp27j`]
The flywheel system of `flybridsystems.com` also captures 70% of the kinetic energy. `www.flybridsystems.com/F1System.html`
Electric regenerative braking salvages 50%. Source: E4tech (2007).

– *Electric batteries capable of delivering 60 kW would weigh about 200 kg.* Good lithium-ion batteries have a specific power of 300 W/kg (Horie et al., 1997; Mindl, 2003).

– *the average new car in the UK emits 168 g CO_2 per km.* This is the figure for the year 2006 (King, 2008). The average emissions of a new passenger vehicle in the USA were 255 g per km (King, 2008).

– *The Toyota Prius has a more-efficient engine.* The Prius's petrol engine uses the Atkinson cycle, in contrast to the conventional Otto cycle. By cunningly mixing electric power and petrol power as the driver's demands change, the Prius gets by with a smaller engine than is normal in a car of its weight, and converts petrol to work more efficiently than a conventional petrol engine.

– *Hybrid technologies give fuel savings of 20% or 30%.* For example, from Hitachi's research report describing hybrid trains (Kaneko et al., 2004): high-efficiency power generation and regenerative braking are "expected to give fuel savings of approximately 20% compared with conventional diesel-powered trains."

127 *Only 8.3% of commuters travel over 30 km to their workplace.* Source: Eddington (2006). The dependence of the range of an electric car on the size of its battery is discussed in Chapter A (p261).

– *Lots of electric vehicles.* They are all listed below, in no particular order. Performance figures are mainly from the manufacturers. As we saw on p127, real-life performance doesn't always match manufacturers' claims.

Th!nk Electric cars from Norway. The five-door Th!nk Ox has a range of 200 km. Its batteries weigh 350 kg, and the car weighs 1500 kg in total. Its energy consumption is approximately 20 kWh per 100 km. `www.think.no`

Electric Smart Car "The electric version is powered by a 40 bhp motor, can go up to 70 miles, and has a top speed of 70 mph. Recharging is done through a standard electrical power point and costs about £1.20, producing the equivalent of 60 g/km of carbon dioxide emissions at the power station. [cf. the equivalent petrol-powered Smart: 116 g/km.] A full recharge takes

Figure 20.37. Th!nk Ox. Photo from `www.think.no`.

about eight hours, but the battery can be topped up from 80%-drained to 80%-charged in about three-and-a-half hours." [www.whatcar.com/news-article.aspx?NA=226488]

Berlingo Electrique 500E, an urban delivery van (figure 20.20), has 27 nicad batteries and a 28 kW motor. It can transport a payload of 500 kg. Top speed: 100 km/h; range: 100 km. 25 kWh per 100 km. (Estimate kindly supplied by a Berlingo owner.) [4wm2w4]

i MiEV This electric car is projected to have a range of 160 km with a 16 kWh battery pack. That's 10 kWh per 100 km – better than the G-Wiz – and whereas it's hard to fit two adult Europeans in a G-Wiz, the Mitsubishi prototype has four doors and four full-size seats (figure 20.38). [658ode]

EV1 The two-seater General Motors EV1 had a range of 120 to 240 km per charge, with nickel-metal hydride batteries holding 26.4 kWh. That's an energy consumption of between 11 and 22 kWh per 100 km.

Lightning (figure 20.39) – has four 120 kW brushless motors, one on each wheel, regenerative braking, and fast-charging Nanosafe lithium titanate batteries. A capacity of 36 kWh gives a range of 200 miles (320 km). That's 11 kWh per 100 km.

Aptera This fantastic slippery fish is a two-seater vehicle, said to have an energy cost of 6 kWh per 100 km. It has a drag coefficient of 0.11 (figure 20.40). Electric and hybrid models are being developed.

Loremo Like the Aptera, the Loremo (figure 20.41) has a small frontal area and small drag coefficient (0.2) and it's going to be available in both fossil-fuel and electric versions. It has two adult seats and two rear-facing kiddie seats. The Loremo EV will have lithium ion batteries and is predicted to have an energy cost of 6 kWh per 100 km, a top speed of 170 km/h, and a range of 153 km. It weighs 600 kg.

eBox The eBox has a lithium-ion battery with a capacity of 35 kWh and a weight of 280 kg; and a range of 140–180 miles. Its motor has a peak power of 120 kW and can produce a sustained power of 50 kW. Energy consumption: 12 kWh per 100 km.

Ze-0 A five-seat, five-door car. Maximum speed: 50 mph. Range: 50 miles. Weight, including batteries: 1350 kg. Lead acid batteries with capacity of 18 kWh. Motor: 15 kW. 22.4 kWh per 100 km.

e500 An Italian Fiat-like car, with two doors and 4 seats. Maximum speed: 60 mph. Range in city driving: 75 miles. Battery: lithium-ion polymer.

MyCar The MyCar is an Italian-designed two-seater. Maximum speed: 40 mph. Maximum range: 60 miles. Lead-acid battery.

Mega City A two-seater car with a maximum continuous power of 4 kW and maximum speed of 40 mph: 11.5 kWh per 100 km. Weight unladen (including batteries) – 725 kg. The lead batteries have a capacity of 10 kWh.

Xebra Is claimed to have a 40 km range from a 4.75 kWh charge. 12 kWh per 100 km. Maximum speed 65 km/h. Lead-acid batteries.

Figure 20.38. The i MiEV from Mitsubishi Motors Corporation. It has a 47 kW motor, weighs 1080 kg, and has a top speed of 130 km/h.

Figure 20.39. Lightning: 11 kWh per 100 km. Photo from www.lightningcarcompany.co.uk.

Figure 20.40. The Aptera. 6 kWh per 100 km. Photo from www.aptera.com.

Figure 20.41. The Loremo. 6 kWh per 100 km. Photo from evolution.loremo.com.

TREV The Two-Seater Renewable Energy Vehicle (TREV) is a prototype developed by the University of South Australia (figure 20.42). This three-wheeler has a range of 150 km, a top speed of 120 km/h, a mass of 300 kg, and lithium-ion polymer batteries weighing 45 kg. During a real 3000 km trip, the energy consumption was 6.2 kWh per 100 km.

Venturi Fetish Has a 28 kWh battery, weighing 248 kg. The car weighs 1000 kg. Range 160–250 km. That's 11–17 kWh per 100 km.
`www.venturifetish.fr/fetish.html`

Toyota RAV4 EV This vehicle – an all-electric mini-SUV – was sold by Toyota between 1997 and 2003 (figure 20.43). The RAV4 EV has 24 12-volt 95Ah NiMH batteries capable of storing 27.4 kWh of energy; and a range of 130 to 190 km. So that's an energy consumption of 14–21 kWh per 100 km. The RAV4 EV was popular with Jersey Police force.

Phoenix SUT – a five-seat "sport utility truck" made in California – has a range of "up to 130 miles" from a 35 kWh lithium-ion battery pack. (That's 17 kWh per 100 km.) The batteries can be recharged from a special outlet in 10 minutes. `www.gizmag.com/go/7446/`

Modec delivery vehicle Modec carries two tons a distance of 100 miles. Kerb weight 3000 kg. `www.modec.co.uk`

Smith Ampere Smaller delivery van, 24 kWh lithium ion batteries. Range "over 100 miles." `www.smithelectricvehicles.com`

Electric minibus From `www.smithelectricvehicles.com`:
40 kWh lithium ion battery pack. 90 kW motor with regenerative brakes. Range "up to 100 miles." 15 seats. Vehicle kerb weight 3026 kg. Payload 1224 kg. That's a vehicle-performance of at best 25 kWh per 100 km. If the vehicle is fully occupied, it could deliver transportation at an impressive cost of 2 kWh per 100 p-km.

Electric coach The Thunder Sky bus has a range of 180 miles and a recharge time of three hours. `www.thunder-sky.com`

Electric scooters The Vectrix is a substantial scooter (figure 20.44). Its battery (nickel metal hydride) has a capacity of 3.7 kWh. It can be driven for up to 68 miles at 25 miles/h (40 km/h), on a two-hour charge from a standard electrical socket. That's 110 km for 3 kWh, or 2.75 kWh per 100 km. It has a maximum speed of 62 mph (100 km/h). It weighs 210 kg and has a peak power of 20 kW. `www.vectrix.com`
The "Oxygen Cargo" is a smaller scooter. It weighs 121 kg, has a 38 mile range, and takes 2–3 hours to charge. Peak power: 3.5 kW; maximum speed 28 mph. It has two lithium-ion batteries and regenerative brakes. The range can be extended by adding extra batteries, which store about 1.2 kWh and weigh 15 kg each. Energy consumption: 4 kWh per 100 km.

Figure 20.42. The TREV. 6 kWh per 100 km. Photo from `www.unisa.edu.au`.

Figure 20.43. Toyota RAV4 EV. Photo by Kenneth Adelman, `www.solarwarrior.com`.

Figure 20.44. Vectrix: 2.75 kWh per 100 km. Photo from `www.vectrix.com`.

129 *the energy-density of compressed-air energy-stores is only about 11–28 Wh per kg.* The theoretical limit, assuming perfect isothermal compression: if 1 m^3 of ambient air is slowly compressed into a 5-litre container at 200 bar, the potential energy stored is 0.16 kWh in 1.2 kg of air. In practice, a 5-litre container appropriate for this sort of pressure weighs about 7.5 kg if made from steel or 2 kg using kevlar or carbon fibre, and the overall energy density achieved would be about 11–28 Wh per kg. The theoretical energy density is the same, whatever the volume of the container.

130 *Arnold Schwarzenegger . . . filling up a hydrogen-powered Hummer.* *Nature* **438**, 24 November 2005. I'm not saying that hydrogen will *never* be useful for transportation; but I would hope that such a distinguished journal as *Nature* would address the hydrogen bandwagon with some critical thought, not only euphoria.

> *Hydrogen and fuel cells are not the way to go. The decision by the Bush administration and the State of California to follow the hydrogen highway is the single worst decision of the past few years.*
>
> James Woolsey, Chairman of the Advisory Board of the US Clean Fuels Foundation, 27th November 2007.

In September 2008, *The Economist* wrote "Almost nobody disputes that . . . eventually most cars will be powered by batteries alone."
On the other hand, to hear more from advocates of hydrogen-based transport, see the Rocky Mountain Institute's pages about the "HyperCar" `www.rmi.org/hypercar/`.

– *In the Clean Urban Transport for Europe project the overall energy required to power the hydrogen buses was between 80% and 200% greater than that of the baseline diesel bus.* Source: CUTE (2006); Binder et al. (2006).

– *Fuelling the hydrogen-powered car made by BMW requires three times more energy than an average car.* Half of the boot of the BMW "Hydrogen 7" car is taken up by its 170-litre hydrogen tank, which holds 8 kg of hydrogen, giving a range of 200 km on hydrogen [`news.bbc.co.uk/1/hi/business/6154212.stm`]. The calorific value of hydrogen is 39 kWh per kg, and the best-practice energy cost of making hydrogen is 63 kWh per kg (made up of 52 kWh of natural gas and 11 kWh of electricity) (CUTE, 2006). So filling up the 8 kg tank has an energy cost of at least 508 kWh; and if that tank indeed delivers 200 km, then the energy cost is 254 kWh per 100 km.

> *The Hydrogen 7 and its hydrogen-fuel-cell cousins are, in many ways, simply flashy distractions.*
>
> David Talbot, MIT Technology Review
> `www.technologyreview.com/Energy/18301/`

Honda's fuel-cell car, the FCX Clarity, weighs 1625 kg, stores 4.1 kg of hydrogen at a pressure of 345 bar, and is said to have a range of 280 miles, consuming 57 miles of road per kg of hydrogen (91 km per kg) in a standard mix of driving conditions [`czjjo`], [`5a3ryx`]. Using the cost for creating hydrogen mentioned above, assuming natural gas is used as the main energy source, this car has a transport cost of 69 kWh per 100 km.

> *Honda might be able to kid journalists into thinking that hydrogen cars are "zero emission" but unfortunately they can't fool the climate.*
>
> Merrick Godhaven

132 *A lithium-ion battery is 3% lithium.* Source: Fisher et al. (2006).

– *Lithium specialist R. Keith Evans says "concerns regarding lithium availability . . . are unfounded."* – Evans (2008).

133 *Two Dutch-built liners known as "The Economy Twins."* `www.ssmaritime.com/rijndam-maasdam.htm`.
QE2: `www.qe2.org.uk`.

134 *Transrapid magnetic levitation train.* `www.transrapid.de`.

21 Smarter heating

Figure 21.1. My house.

In the last chapter, we learned that electrification could shrink transport's energy consumption to one fifth of its current levels; and that public transport and cycling can be about 40 times more energy-efficient than car-driving. How about heating? What sort of energy-savings can technology or lifestyle-change offer?

The power used to heat a building is given by multiplying together three quantities:

$$\text{power used} = \frac{\text{average temperature difference} \times \text{leakiness of building}}{\text{efficiency of heating system}}.$$

Let me explain this formula (which is discussed in detail in Chapter E) with an example. My house is a three-bedroom semi-detached house built about 1940 (figure 21.1). The average temperature difference between the inside and outside of the house depends on the setting of the thermostat and on the weather. If the thermostat is permanently at 20 °C, the average temperature difference might be 9 °C. The *leakiness* of the building describes how quickly heat gets out through walls, windows, and cracks, in response to a temperature difference. The leakiness is sometimes called the *heat-loss coefficient* of the building. It is measured in kWh per day per degree of temperature difference. In Chapter E, I calculate that the leakiness of my house in 2006 was 7.7 kWh/d/°C. The product

$$\text{average temperature difference} \times \text{leakiness of building}$$

is the rate at which heat flows out of the house by conduction and ventilation. For example, if the average temperature difference is 9 °C then the heat loss is

$$9\,^\circ\text{C} \times 7.7\,\text{kWh/d/}^\circ\text{C} \simeq 70\,\text{kWh/d}.$$

Finally, to calculate the power required, we divide this heat loss by the efficiency of the heating system. In my house, the condensing gas boiler has an efficiency of 90%, so we find:

$$\text{power used} = \frac{9\,^\circ\text{C} \times 7.7\,\text{kWh/d/}^\circ\text{C}}{0.9} = 77\,\text{kWh/d}.$$

That's bigger than the space-heating requirement we estimated in Chapter 7. It's bigger for two reasons: first, this formula assumes that all the heat is supplied by the boiler, whereas in fact some heat is supplied by incidental heat gains from occupants, gadgets, and the sun; second, in Chapter 7 we assumed that a person kept just two rooms at 20 °C all the time; keeping an entire house at this temperature all the time would require more.

OK, how can we reduce the power used by heating? Well, obviously, there are three lines of attack.

1. Reduce the average temperature difference. This can be achieved by turning thermostats down (or, if you have friends in high places, by changing the weather).
2. Reduce the leakiness of the building. This can be done by improving the building's insulation – think triple glazing, draught-proofing, and fluffy blankets in the loft – or, more radically, by demolishing the building and replacing it with a better insulated building; or perhaps by living in a building of smaller size per person. (Leakiness tends to be bigger, the larger a building's floor area, because the areas of external wall, window, and roof tend to be bigger too.)
3. Increase the efficiency of the heating system. You might think that 90% sounds hard to beat, but actually we can do much better.

Cool technology: the thermostat

The thermostat (accompanied by woolly jumpers) is hard to beat, when it comes to value-for-money technology. You turn it down, and your building uses less energy. Magic! In Britain, for every degree that you turn the thermostat down, the heat loss decreases by about 10%. Turning the thermostat down from 20 °C to 15 °C would nearly halve the heat loss. Thanks to incidental heat gains by the building, the savings in heating power will be even bigger than these reductions in heat loss.

Unfortunately, however, this remarkable energy-saving technology has side-effects. Some humans call turning the thermostat down a lifestyle change, and are not happy with it. I'll make some suggestions later about how to sidestep this lifestyle issue. Meanwhile, as proof that "the most important smart component in a building with smart heating is the occupant," figure 21.2 shows data from a Carbon Trust study, observing the heat consumption in twelve identical modern houses. This study permits us to gawp at the family at number 1, whose heat consumption is twice as big as that of Mr. and Mrs. Woolly at number 12. However, we should pay attention to the numbers: the family at number 1 are using 43 kWh per day. But if this is shocking, hang on – a moment ago, didn't I estimate that *my* house might use more than that? Indeed, my average gas consumption from 1993 to 2003 was a little more than 43 kWh per day (figure 7.10, p53), and I thought I was a frugal person! The problem is the *house*. All the modern houses in the Carbon Trust study had a leakiness of 2.7 kWh/d/°C, but my house had a leakiness of 7.7 kWh/d/°C! People who live in leaky houses...

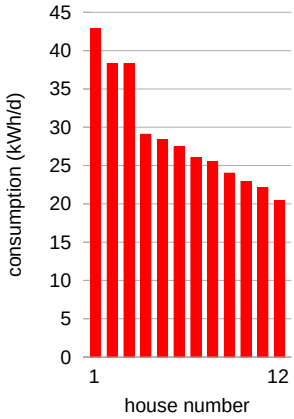


Figure 21.2. Actual heat consumption in 12 identical houses with identical heating systems. All houses had floor area 86 m^2 and were designed to have a leakiness of 2.7 kWh/d/°C. Source: Carbon Trust (2007).

The war on leakiness

What can be done with leaky old houses, apart from calling in the bulldozers? Figure 21.3 shows estimates of the space heating required in old

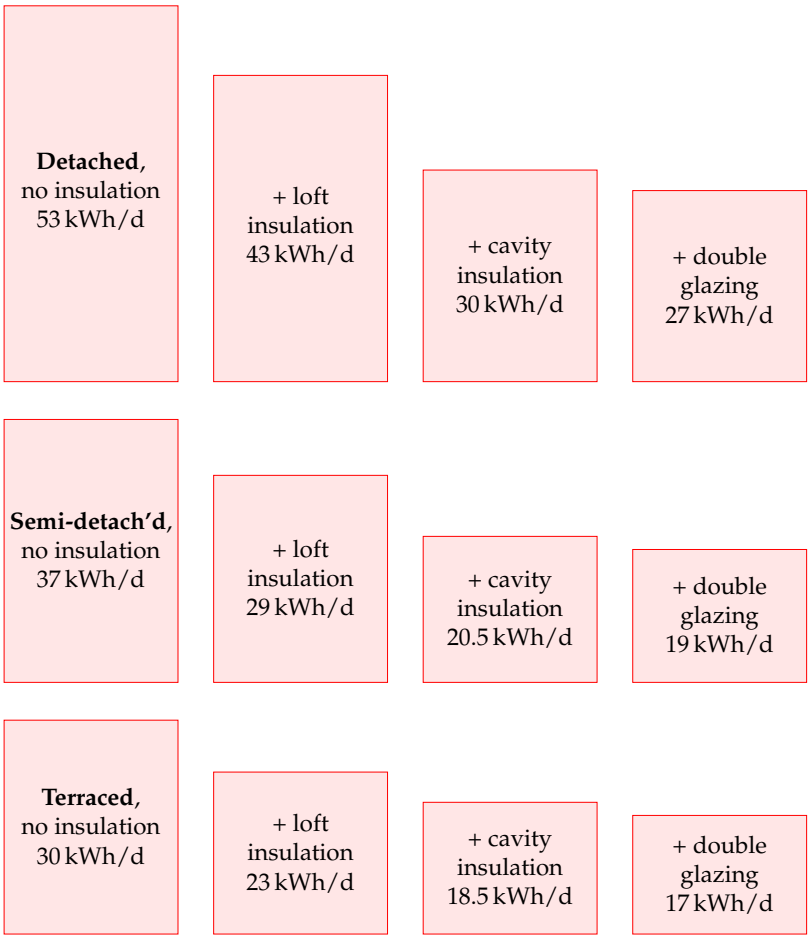


Figure 21.3. Estimates of the space heating required in a range of UK houses. From Eden and Bending (1985).

detached, semi-detached, and terraced houses as progressively more effort is put into patching them up. Adding loft insulation and cavity-wall insulation reduces heat loss in a typical old house by about 25%. Thanks to incidental heat gains, this 25% reduction in heat loss translates into roughly a 40% reduction in heating consumption.

Let's put these ideas to the test.

A case study

I introduced you to my house on page 53. Let's pick up the story. In 2004 I had a condensing boiler installed, replacing the old gas boiler. (Condensing boilers use a heat-exchanger to transfer heat from the exhaust gases to incoming air.) At the same time I removed the house's hot-water tank (so hot water is now made only on demand), and I put thermostats on all the bedroom radiators. Along with the new condensing boiler came a

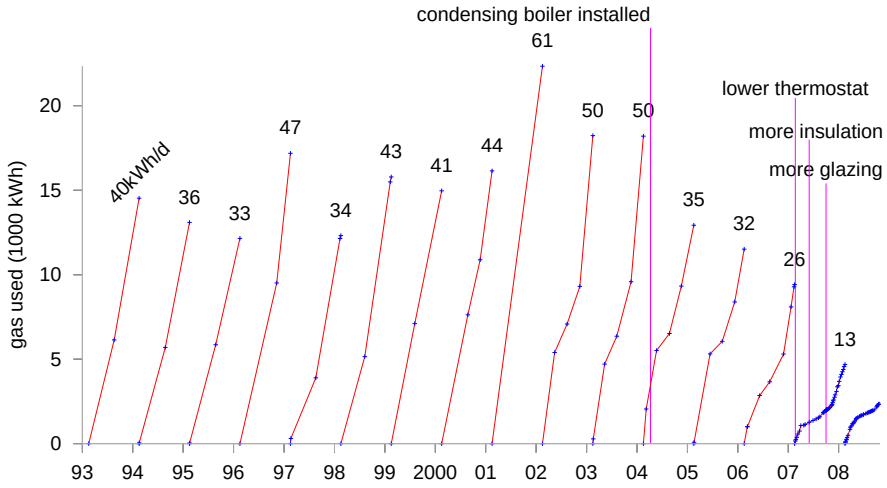


Figure 21.4. My domestic gas consumption, each year from 1993 to 2007. Each line shows the cumulative consumption during one year in kWh. The number at the end of each year is the average rate of consumption for that year, in kWh per day. Meter-readings are indicated by the blue points. Evidently, the more frequently I read my meter, the less gas I use!

new heating controller that allows me to set different target temperatures for different times of day. With these changes, my consumption decreased from an average of 50 kWh/d to about 32 kWh/d.

This reduction from 50 to 32 kWh/d is quite satisfying, but it's not enough, if the aim is to reduce one's fossil fuel footprint below one ton of CO_2 per year. 32 kWh/d of gas corresponds to over 2 tons CO_2 per year.

In 2007, I started paying more careful attention to my energy meters. I had cavity-wall insulation installed (figure 21.5) and improved my loft insulation. I replaced the single-glazed back door by a double-glazed door, and added an extra double-glazed door to the front porch (figure 21.6). Most important of all, I paid more attention to my thermostat settings. This attentiveness has led to a further halving in gas consumption. The latest year's consumption was 13 kWh/d!

Because this case study is such a hodge-podge of building modifications and behaviour changes, it's hard to be sure which changes were the most important. According to my calculations (in Chapter E), the improvements in insulation reduced the leakiness by 25%, from 7.7 kWh/d/°C to 5.8 kWh/d/°C. This is still much leakier than any modern house. It's frustratingly difficult to reduce the leakiness of an already-built house!

So, my main tip is cunning thermostat management. What's a reasonable thermostat setting to aim for? Nowadays many people seem to think that 17 °C is unbearably cold. However, the average winter-time temperature in British houses in 1970 was 13 °C! A human's perception of whether they feel warm depends on what they are doing, and what they've been doing for the last hour or so. My suggestion is, *don't think in terms of a thermostat setting.* Rather than fixing the thermostat to a single value, try just leaving it at a really low value most of the time (say 13 or 15 °C), and turn it up temporarily whenever you feel cold. It's like the lights in a library. If you allow yourself to ask the question "what is the right light level in the bookshelves?" then you'll no doubt answer "bright enough to read the

Figure 21.5. Cavity-wall insulation going in.

Figure 21.6. A new front door.

book titles," and you'll have bright lights on all the time. But that question presumes that we have to fix the light level; and we don't have to. We can fit light switches that the reader can turn on, and that switch themselves off again after an appropriate time. Similarly, thermostats don't need to be left up at 20 °C all the time.

Before leaving the topic of thermostat settings, I should mention air-conditioning. Doesn't it drive you crazy to go into a building in summer where the thermostat of the air-conditioning is set to 18 °C? These loony building managers are subjecting everyone to temperatures that in wintertime they would whinge are too cold! In Japan, the government's "Cool-Biz" guidelines recommend that air-conditioning be set to 28 °C (82 F).

Better buildings

If you get the chance to build a new building then there are lots of ways to ensure its heating consumption is much smaller than that of an old building. Figure 21.2 gave evidence that modern houses are built to much better insulation standards than those of the 1940s. But the building standards in Britain could be still better, as Chapter E discusses. The three key ideas for the best results are: (1) have really thick insulation in floors, walls, and roofs; (2) ensure the building is completely sealed and use active ventilation to introduce fresh air and remove stale and humid air, with heat exchangers passively recovering much of the heat from the removed air; (3) design the building to exploit sunshine as much as possible.

The energy cost of heat

So far, this chapter has focused on temperature control and leakiness. Now we turn to the third factor in the equation:

$$\text{power used} = \frac{\text{average temperature difference} \times \text{leakiness of building}}{\text{efficiency of heating system}}.$$

How efficiently can heat be produced? Can we obtain heat on the cheap? Today, building-heating in Britain is primarily delivered by burning a fossil fuel, natural gas, in boilers with efficiencies of 78%–90%. Can we get off fossil fuels at the same time as making building-heating more efficient?

One technology that is held up as an answer to Britain's heating problem is called "combined heat and power" (CHP), or its cousin, "micro-CHP." I will explain combined heat and power now, but I've come to the conclusion that it's a bad idea, because there's a better technology for heating, called heat pumps, which I'll describe in a few pages.

Figure 21.7. Eggborough. Not a power station participating in smart heating.

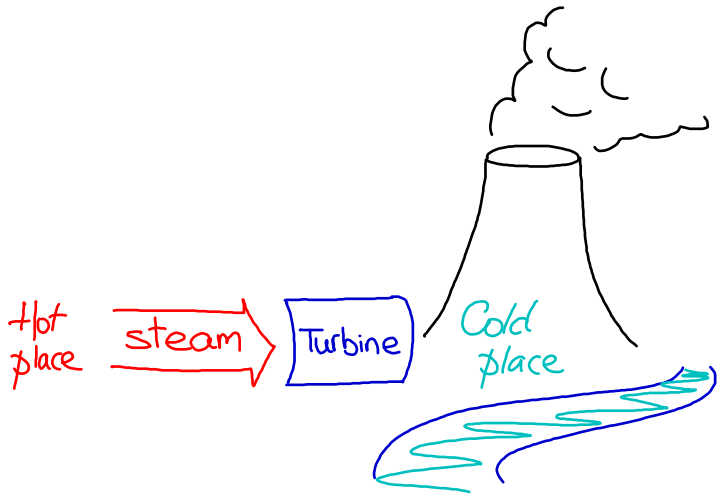


Figure 21.8. How a power station works. There has to be a cold place to condense the steam to make the turbine go round. The cold place is usually a cooling tower or river.

Combined heat and power

The standard view of conventional big centralised power stations is that they are terribly inefficient, chucking heat willy-nilly up chimneys and cooling towers. A more sophisticated view recognizes that to turn thermal energy into electricity, we inevitably have to dump heat in a cold place (figure 21.8). That is how heat engines work. There *has* to be a cold place. But surely, it's argued, we could use *buildings* as the dumping place for this "waste" heat instead of cooling towers or sea water? This idea is called "combined heat and power" (CHP) or cogeneration, and it's been widely used in continental Europe for decades – in many cities, a big power station is integrated with a district heating system. Proponents of the modern incarnation of combined heat and power, "micro-CHP," suggest that tiny power stations should be created within single buildings or small collections of buildings, delivering heat and electricity to those buildings, and exporting some electricity to the grid.

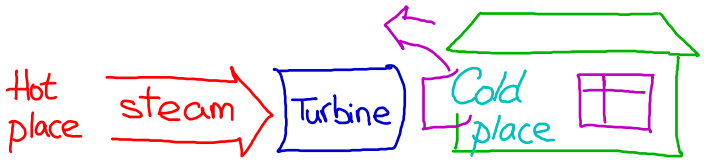


Figure 21.9. Combined heat and power. District heating absorbs heat that would have been chucked up a cooling tower.

There's certainly some truth in the view that Britain is rather backward when it comes to district heating and combined heat and power, but discussion is hampered by a general lack of numbers, and by two particular errors. First, when comparing different ways of using fuel, the wrong measure of "efficiency" is used, namely one that weights electricity as having equal value to heat. The truth is, electricity is more valuable than heat. Second, it's widely assumed that the "waste" heat in a traditional power

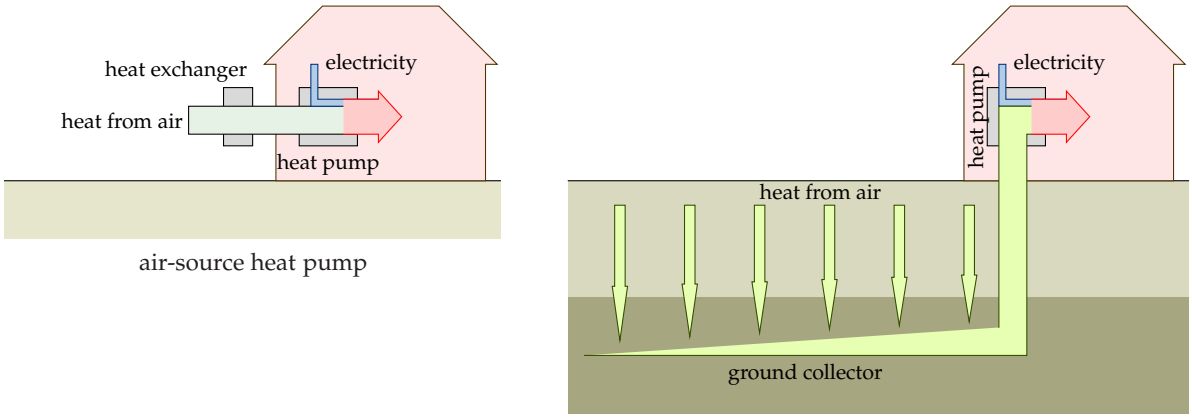


Figure 21.10. Heat pumps.

station could be captured for a useful purpose *without impairing the power station's electricity production*. This sadly is not true, as the numbers will show. Delivering useful heat to a customer always reduces the electricity produced to some degree. The true net gains from combined heat and power are often much smaller than the hype would lead you to believe.

A final impediment to rational discussion of combined heat and power is a myth that has grown up recently, that decentralizing a technology somehow makes it greener. So whereas big centralized fossil fuel power stations are "bad," flocks of local micro-power stations are imbued with goodness. But if decentralization is actually a good idea then "small is beautiful" should be evident in the numbers. Decentralization should be able to stand on its own two feet. And what the numbers actually show is that *centralized* electricity generation has many benefits in both economic and energy terms. Only in large buildings is there any benefit to local generation, and usually that benefit is only about 10% or 20%.

The government has a target for growth of combined heat and power to 10 GW of electrical capacity by 2010, but I think that growth of gas-powered combined heat and power would be a mistake. Such combined heat and power is not green: it uses fossil fuel, and it locks us into continued use of fossil fuel. Given that heat pumps are a better technology, I believe we should leapfrog over gas-powered combined heat and power and go directly for heat pumps.

Heat pumps

Like district heating and combined heat and power, heat pumps are already widely used in continental Europe, but strangely rare in Britain. Heat pumps are back-to-front refrigerators. Feel the back of your refrigerator: it's *warm*. A refrigerator moves heat from one place (its inside) to

another (its back panel). So one way to heat a building is to turn a refrigerator inside-out – put the *inside* of the refrigerator in the garden, thus cooling the garden down; and leave the back panel of the refrigerator in your kitchen, thus warming the house up. What isn't obvious about this whacky idea is that it is a really efficient way to warm your house. For every kilowatt of power drawn from the electricity grid, the back-to-front refrigerator can pump three kilowatts of heat from the garden, so that a total of four kilowatts of heat gets into your house. So heat pumps are roughly four times as efficient as a standard electrical bar-fire. Whereas the bar-fire's efficiency is 100%, the heat pump's is 400%. The efficiency of a heat pump is usually called its *coefficient of performance* or CoP. If the efficiency is 400%, the coefficient of performance is 4.

Heat pumps can be configured in various ways (figure 21.10). A heat pump can cool down the *air* in your garden using a heat-exchanger (typically a 1-metre tall white box, figure 21.11), in which case it's called an air-source heat pump. Alternatively, the pump may cool down the *ground* using big loops of underground plumbing (many tens of metres long), in which case it's called a ground-source heat pump. Heat can also be pumped from rivers and lakes.

Some heat pumps can pump heat in either direction. When an air-source heat pump runs in reverse, it uses electricity to warm up the *outside* air and cool down the air *inside* your building. This is called air-conditioning. Many air-conditioners are indeed heat-pumps working in precisely this way. Ground-source heat pumps can also work as air-conditioners. So a single piece of hardware can be used to provide winter heating and summer cooling.

People sometimes say that ground-source heat pumps use "geothermal energy," but that's not the right name. As we saw in Chapter 16, geothermal energy offers only a tiny trickle of power per unit area (about 50 mW/m^2), in most parts of the world; heat pumps have nothing to do with this trickle, and they can be used both for heating and for cooling. Heat pumps simply use the ground as a place to suck heat from, or to dump heat into. When they steadily suck heat, that heat is actually being replenished by warmth from the sun.

There's two things left to do in this chapter. We need to compare heat pumps with combined heat and power. Then we need to discuss what are the limits to ground-source heat pumps.

Figure 21.11. The inner and outer bits of an air-source heat pump that has a coefficient of performance of 4. The inner bit is accompanied by a ball-point pen, for scale. One of these Fujitsu units can deliver 3.6 kW of heating when using just 0.845 kW of electricity. It can also run in reverse, delivering 2.6 kW of cooling when using 0.655 kW of electricity.

Heat pumps, compared with combined heat and power

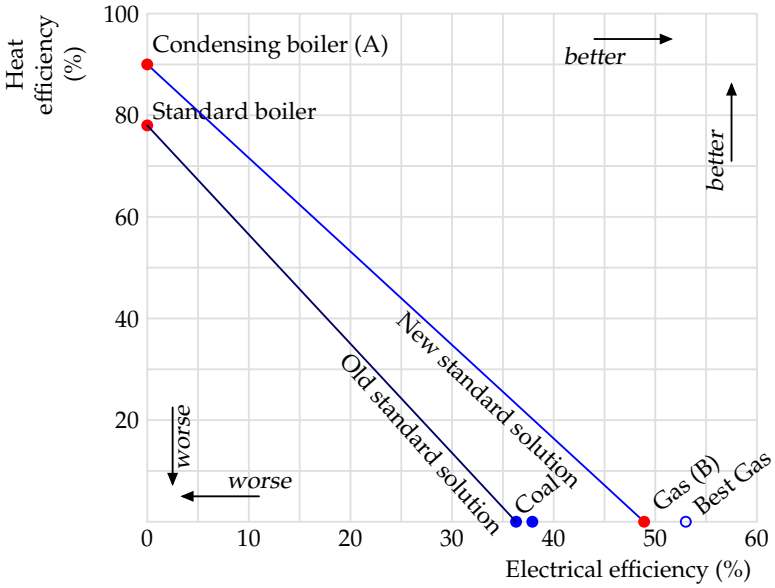
I used to think that combined heat and power was a no-brainer. "Obviously, we should use the discarded heat from power stations to heat buildings rather than just chucking it up a cooling tower!" However, looking carefully at the numbers describing the performance of real CHP systems, I've come to the conclusion that there are better ways of providing electric-

ity and building-heating.

I'm going to build up a diagram in three steps. The diagram shows how much electrical energy or heat energy can be delivered from chemical energy. The horizontal axis shows the electrical efficiency and the vertical axis shows the heat efficiency.

The standard solution with no CHP

In the first step, we show simple power stations and heating systems that deliver pure electricity or pure heat.

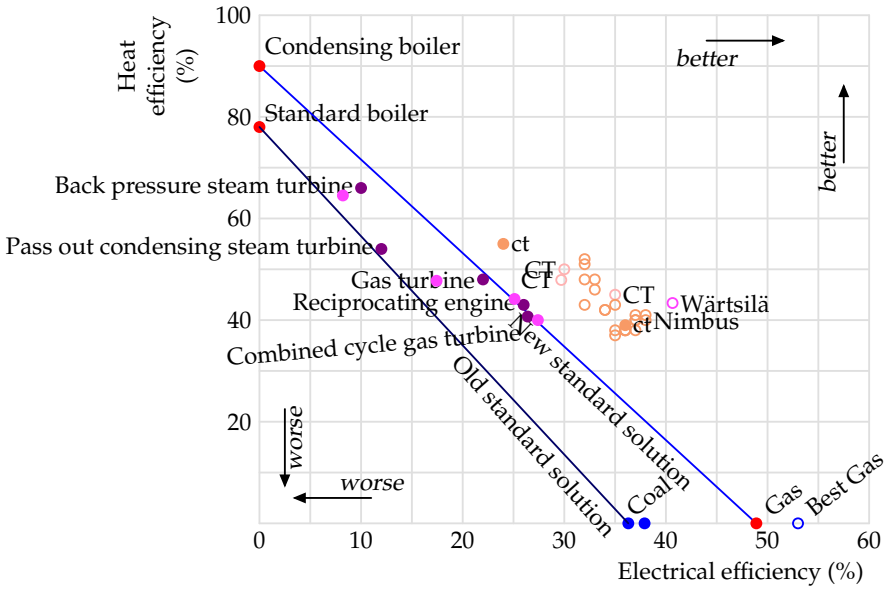


Condensing boilers (the top-left dot, A) are 90% efficient because 10% of the heat goes up the chimney. Britain's gas power stations (the bottom-right dot, B) are currently 49% efficient at turning the chemical energy of gas into electricity. If you want any mix of electricity and heat from natural gas, you can obtain it by burning appropriate quantities of gas in the electricity power station and in the boiler. Thus the new standard solution can deliver any electrical efficiency and heat efficiency on the line A–B by making the electricity and heat using two separate pieces of hardware.

To give historical perspective, the diagram also shows the old standard heating solution (an ordinary non-condensing boiler, with an efficiency of 79%) and the standard way of making electricity a few decades ago (a coal power station with an electrical efficiency of 37% or so).

Combined heat and power

Next we add combined heat and power systems to the diagram. These simultaneously deliver, from chemical energy, both electricity and heat.



Each of the filled dots shows actual average performances of CHP systems in the UK, grouped by type. The hollow dots marked "CT" show the performances of ideal CHP systems quoted by the Carbon Trust; the hollow dots marked "Nimbus" are from a manufacturer's product specifications. The dots marked "ct" are the performances quoted by the Carbon Trust for two real systems (at Freeman Hospital and Elizabeth House).

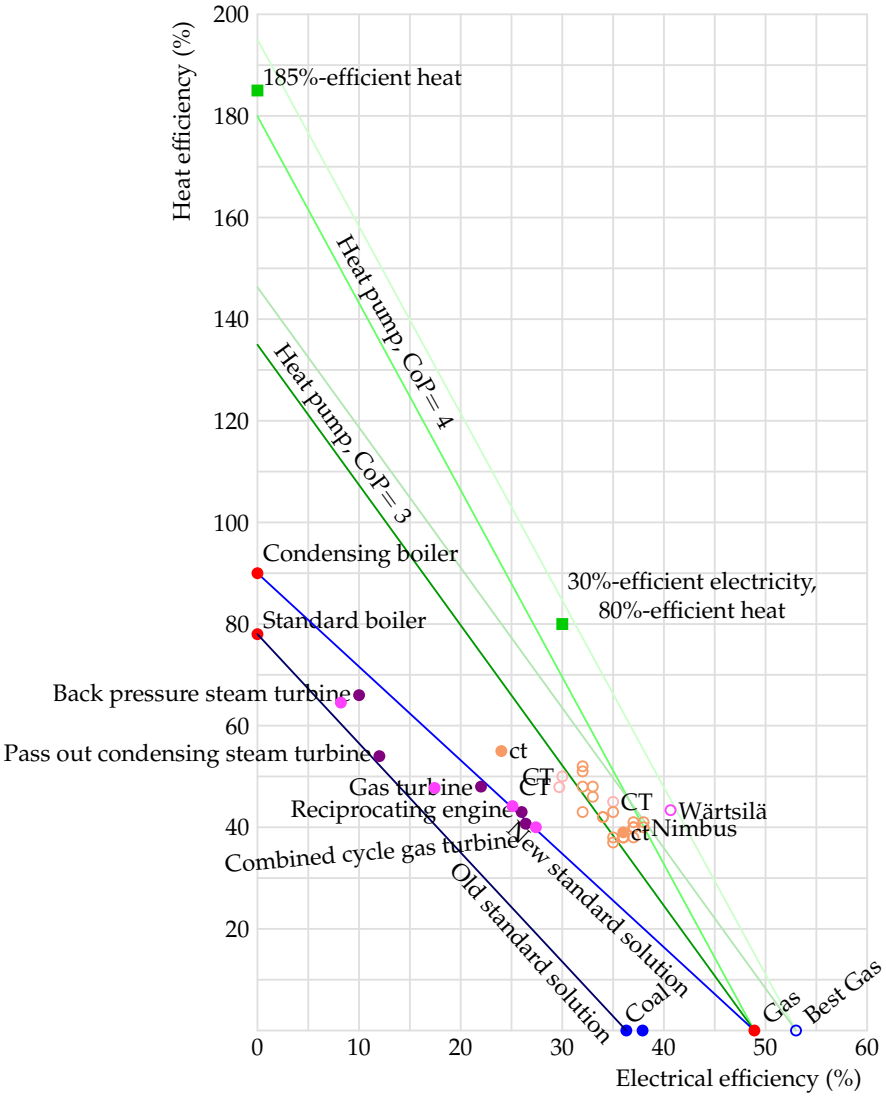
The main thing to notice in this diagram is that the electrical efficiencies of the CHP systems are significantly smaller than the 49% efficiency delivered by single-minded electricity-only gas power stations. So the heat is not a "free by-product." Increasing the heat production hurts the electricity production.

It's common practice to lump together the two numbers (the efficiency of electricity production and heat production) into a single "total efficiency" – for example, the back pressure steam turbines delivering 10% electricity and 66% heat would be called "76% efficient," but I think this is a misleading summary of performance. After all, by this measure, the 90%-efficient condensing boiler is "more efficient" than all the CHP systems! The fact is, electrical energy is more valuable than heat.

Many of the CHP points in this figure are superior to the "old standard way of doing things" (getting electricity from coal and heat from standard boilers). And the ideal CHP systems are slightly superior to the "new standard way of doing things" (getting electricity from gas and heat from condensing boilers). But we must bear in mind that this slight superiority comes with some drawbacks – a CHP system delivers heat only to the places it's connected to, whereas condensing boilers can be planted anywhere with a gas main; and compared to the standard way of doing things, CHP systems are not so flexible in the mix of electricity and heat

they deliver; a CHP system will work best only when delivering a particular mix; this inflexibility leads to inefficiencies at times when, for example, excess heat is produced; in a typical house, much of the electricity demand comes in relatively brief spikes, bearing little relation to heating demand. A final problem with some micro-CHP systems is that when they have excess electricity to share, they may do a poor job of delivering power to the network.

Finally we add in heat pumps, which use electricity from the grid to pump ambient heat into buildings.



The steep green lines show the combinations of electricity and heat that you can obtain assuming that heat pumps have a coefficient of per-

formance of 3 or 4, assuming that the extra electricity for the heat pumps is generated by an average gas power station or by a top-of-the-line gas power station, and allowing for 8% loss in the national electricity network between the power station and the building where the heat pumps pump heat. The top-of-the-line gas power station's efficiency is 53%, assuming it's running optimally. (I imagine the Carbon Trust and Nimbus made a similar assumption when providing the numbers used in this diagram for CHP systems.) In the future, heat pumps will probably get even better than I assumed here. In Japan, thanks to strong legislation favouring efficiency improvements, heat pumps are now available with a coefficient of performance of 4.9.

Notice that heat pumps offer a system that can be "better than 100%-efficient." For example the "best gas" power station, feeding electricity to heat pumps can deliver a combination of 30%-efficient electricity and 80%-efficient heat, a "total efficiency" of 110%. No plain CHP system could ever match this performance.

Let me spell this out. Heat pumps are superior in efficiency to condensing boilers, even if the heat pumps are powered by electricity from a power station burning natural gas. If you want to heat lots of buildings using natural gas, you could install condensing boilers, which are "90% efficient," or you could send the same gas to a new gas power station making electricity and install electricity-powered heat pumps in all the buildings; the second solution's efficiency would be somewhere between 140% and 185%. It's not necessary to dig big holes in the garden and install underfloor heating to get the benefits of heat pumps; the best air-source heat pumps (which require just a small external box, like an air-conditioner's) can deliver hot water to normal radiators with a coefficient of performance above 3. The air-source heat pump in figure 21.11 (p147) directly delivers warm air to an office.

I thus conclude that combined heat and power, even though it sounds a good idea, is probably not the best way to heat buildings and make electricity using natural gas, assuming that air-source or ground-source heat pumps can be installed in the buildings. The heat-pump solution has further advantages that should be emphasized: heat pumps can be located in any buildings where there is an electricity supply; they can be driven by any electricity source, so they keep on working when the gas runs out or the gas price goes through the roof; and heat pumps are flexible: they can be turned on and off to suit the demand of the building occupants.

I emphasize that this critical comparison does not mean that CHP is always a bad idea. What I'm comparing here are methods for heating ordinary buildings, which requires only very low-grade heat. CHP can also be used to deliver higher-grade heat to industrial users (at 200 °C, for example). In such industrial settings, heat pumps are unlikely to compete so well because their coefficient of performance would be lower.

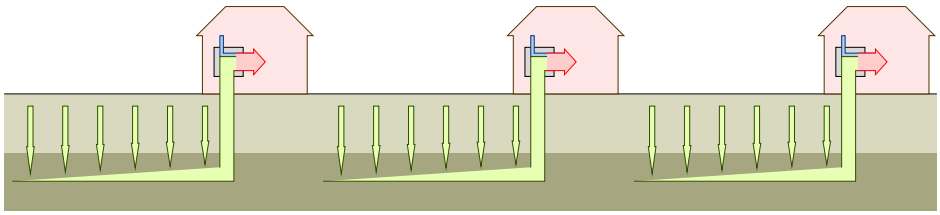


Figure 21.12. How close together can ground-source heat pumps be packed?

Limits to growth (of heat pumps)

Because the temperature of the ground, a few metres down, stays sluggishly close to 11 °C, whether it's summer or winter, the ground is theoretically a better place for a heat pump to grab its heat than the air, which in midwinter may be 10 or 15 °C colder than the ground. So heat-pump advisors encourage the choice of ground-source over air-source heat pumps, where possible. (Heat pumps work less efficiently when there's a big temperature difference between the inside and outside.)

However, the ground is not a limitless source of heat. The heat has to come from somewhere, and ground is not a very good thermal conductor. If we suck heat too fast from the ground, the ground will become as cold as ice, and the advantage of the ground-source heat pump will be diminished.

In Britain, the main purpose of heat pumps would be to get heat into buildings in the winter. The ultimate source of this heat is the sun, which replenishes heat in the ground by direct radiation and by conduction through the air. The rate at which heat is sucked from the ground must satisfy two constraints: it must not cause the ground's temperature to drop too low during the winter; and the heat sucked in the winter must be replenished somehow during the summer. If there's any risk that the *natural* trickling of heat in the summer won't make up for the heat removed in the winter, then the replenishment must be driven *actively* – for example by running the system in reverse in summer, putting heat down into the ground (and thus providing air-conditioning up top).

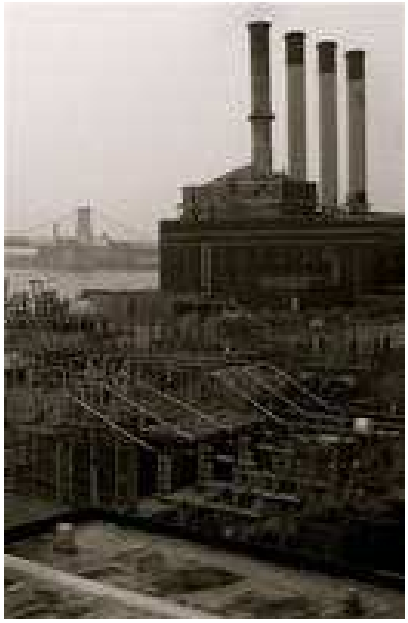
Let's put some numbers into this discussion. How big a piece of ground does a ground-source heat pump need? Assume that we have a neighbourhood with quite a high population density – say 6200 people per km^2 (160 m^2 per person), the density of a typical British suburb. Can *everyone* use ground-source heat pumps, without using active summer replenishment? A calculation in Chapter E (p303) gives a tentative answer of *no*: if we wanted everyone in the neighbourhood to be able to pull from the ground a heat flow of about 48 kWh/d per person (my estimate of our typical winter heat demand), we'd end up freezing the ground in the winter. Avoiding unreasonable cooling of the ground requires that the sucking rate be less than 12 kWh/d per person. So if we switch to ground-source heat pumps, we should plan to include substantial summer heat-dumping in the design, so as to refill the ground with heat for use in the winter. This summer heat-dumping could use heat from air-conditioning, or heat from

	area per person (m^2)
Bangalore	37
Manhattan	39
Paris	40
Chelsea	66
Tokyo	72
Moscow	97
Taipei	104
The Hague	152
San Francisco	156
Singapore	156
Cambridge MA	164
Sydney	174
Portsmouth	213

Table 21.13. Some urban areas per person.

roof-mounted solar water-heating panels. (Summer solar heat is stored in the ground for subsequent use in winter by Drake Landing Solar Community in Canada [www.dlsc.ca].) Alternatively, we should expect to need to use some air-source heat pumps too, and then we'll be able to get all the heat we want – as long as we have the electricity to pump it. In the UK, air temperatures don't go very far below freezing, so concerns about poor winter-time performance of air-source pumps, which might apply in North America and Scandanavia, probably do not apply in Britain.

My conclusion: can we reduce the energy we consume for heating? Yes. Can we get off fossil fuels at the same time? Yes. Not forgetting the low-hanging fruit – building-insulation and thermostat shenanigans – we should replace all our fossil-fuel heaters with electric-powered heat pumps; we can reduce the energy required to 25% of today's levels. Of course this plan for electrification would require more electricity. But even if the extra electricity came from gas-fired power stations, that would still be a much better way to get heating than what we do today, simply setting fire to the gas. Heat pumps are future-proof, allowing us to heat buildings efficiently with electricity from any source.



Nay-sayers object that the coefficient of performance of air-source heat pumps is lousy – just 2 or 3. But their information is out of date. If we are careful to buy top-of-the-line heat pumps, we can do much better. The Japanese government legislated a decade-long efficiency drive that has greatly improved the performance of air-conditioners; thanks to this drive, there are now air-source heat pumps with a coefficient of performance of 4.9; these heat pumps can make hot water as well as hot air.

Another objection to heat pumps is "oh, we can't approve of people fitting efficient air-source heaters, because they might use them for air-conditioning in the summer." Come on – I hate gratuitous air-conditioning as much as anyone, but these heat pumps are four times more efficient than any other winter heating method! Show me a better choice. Wood pellets? Sure, a few wood-scavengers can burn wood. But there is not enough wood for everyone to do so. For forest-dwellers, there's wood. For everyone else, there's heat pumps.

Notes and further reading

page no.

142 *Loft and cavity insulation reduces heat loss in a typical old house by about a quarter.* Eden and Bending (1985).

143 *The average internal temperature in British houses in 1970 was 13°C!* Source: Dept. of Trade and Industry (2002a, para 3.11)

145 *Britain is rather backward when it comes to district heating and combined heat and power.* The rejected heat from UK power stations could meet the

heating needs of the entire country (Wood, 1985). In Denmark in 1985, district heating systems supplied 42% of space heating, with heat being transmitted 20 km or more in hot pressurized water. In West Germany in 1985, 4 million dwellings received 7 kW per dwelling from district heating. Two thirds of the heat supplied was from power stations. In Vasteras, Sweden in 1985, 98% of the city's heat was supplied from power stations.

147 *Heat pumps are roughly four times as efficient as a standard electrical barfire.* See `www.gshp.org.uk`.
Some heat pumps available in the UK already have a coefficient of peformance bigger than 4.0 [`yok2nw`]. Indeed there is a government subsidy for water-source heat pumps that applies only to pumps with a coefficient of peformance better than 4.4 [`2dtx8z`].
Commercial ground-source heat pumps are available with a coefficient of performance of 5.4 for cooling and 4.9 for heating [`2fd8ar`].

153 *Air-source heat pumps with a coefficient of performance of 4.9...* According to HPTCJ (2007), heat pumps with a coefficient of performance of 6.6 have been available in Japan since 2006. The performance of heat pumps in Japan improved from 3 to 6 within a decade thanks to government regulations. HPTCJ (2007) describe an air-source-heat-pump water-heater called Eco Cute with a coefficient of performance of 4.9. The Eco Cute came on the market in 2001. `www.ecosystem-japan.com`.

Further reading on heat pumps: European Heat Pump Network `ehpn.fiz-karlsruhe.de/en/`, `www.kensaengineering.com`, `www.heatking.co.uk`, `www.iceenergy.co.uk`.

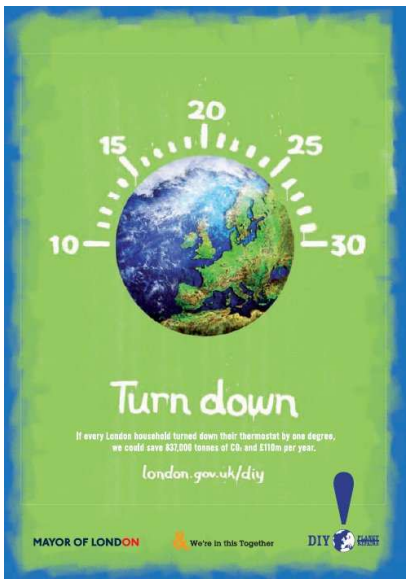


Figure 21.14. Advertisement from the Mayor of London's "DIY planet repairs" campaign of 2007. The text reads "**Turn down**. If every London household turned down their thermostat by one degree, we could save 837 000 tons of CO_2 and £110m per year." [`london.gov.uk/diy`] Expressed in savings per person, that's 0.12 t CO_2 per year per person. That's about 1% of one person's total (11 t), so this *is* good advice. Well done, Ken!

22 *Efficient electricity use*

Can we cut electricity use? Yes, switching off gadgets when they're not in use is an easy way to make a difference. Energy-efficient light bulbs will save you electricity too.

We already examined gadgets in Chapter 11. Some gadgets are unimportant, but some are astonishing guzzlers. The laser-printer in my office, sitting there doing nothing, is slurping 17 W – nearly 0.5 kWh per day! A friend bought a lamp from IKEA. Its awful adaptor (figure 22.1) guzzles 10 W (0.25 kWh per day) whether or not the lamp is on. If you add up a few stereos, DVD players, cable modems, and wireless devices, you may even find that half of your home electricity consumption can be saved.

According to the International Energy Agency, standby power consumption accounts for roughly 8% of residential electricity demand. In the UK and France, the average standby power is about 0.75 kWh/d per household. The problem isn't standby itself – it's the shoddy way in which standby is implemented. It's perfectly possible to make standby systems that draw less than 0.01 W; but manufacturers, saving themselves a penny in the manufacturing costs, are saddling the consumer with an annual cost of pounds.

Figure 22.1. An awful AC lamp-adaptor from IKEA – the adaptor uses nearly 10 W even when the lamp is switched off!

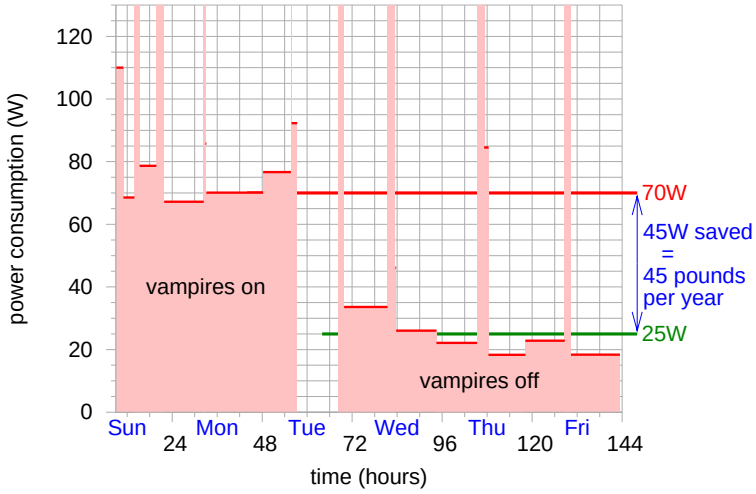


Figure 22.2. Efficiency in the offing. I measured the electricity savings from switching off vampires during a week when I was away at work most of each day, so both days and nights were almost devoid of useful activity, except for the fridge. The brief little blips of consumption are caused by the microwave, toaster, washing machine, or vacuum cleaner. On the Tuesday I switched off most of my vampires: two stereos, a DVD player, a cable modem, a wireless router, and an answering machine. The red line shows the trend of "nobody-at-home" consumption before, and the green line shows the "nobody-at-home" consumption after this change. Consumption fell by 45 W, or 1.1 kWh per day.

A vampire-killing experiment

Figure 22.2 shows an experiment I did at home. First, for two days, I measured the power consumption when I was out or asleep. Then, switching

off all the gadgets that I normally left on, I measured again for three more days. I found that the power saved was 45 W – which is worth £45 per year if electricity costs 11p per unit.

Since I started paying attention to my meter readings, my total electricity consumption has halved (figure 22.3). I've cemented this saving in place by making a habit of reading my meters every week, so as to check that the electricity-sucking vampires have been banished. If this magic trick could be repeated in all homes and all workplaces, we could obviously make substantial savings. So a bunch of us in Cambridge are putting together a website devoted to making regular meter-reading fun and informative. The website, `ReadYourMeter.org`, aims to help people carry out similar experiments to mine, make sense of the resulting numbers, and get a warm fuzzy feeling from using less.

I do hope that this sort of smart-metering activity will make a difference. In the future cartoon-Britain of 2050, however, I've assumed that all such electricity savings are cancelled out by the miracle of growth. Growth is one of the tenets of our society: people are going to be wealthier, and thus able to play with more gadgets. The demand for ever-more-superlative computer games forces computers' power consumption to increase. Last decade's computers used to be thought pretty neat, but now they are found useless, and must be replaced by faster, hotter machines.

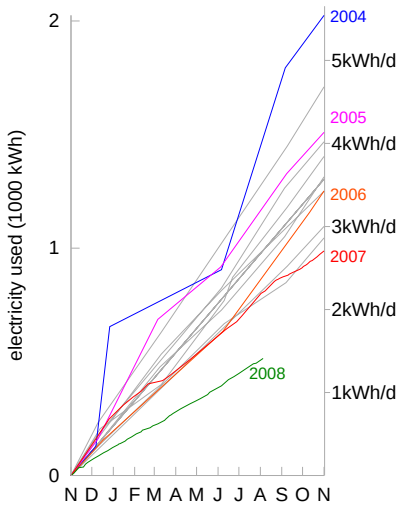


Figure 22.3. My cumulative domestic electricity consumption, in kWh, each year from 1993 to 2008. The grey lines show years from 1993 to 2003. (I haven't labelled these with their years, to avoid clutter.) The coloured lines show the years 2004 onwards. The scale on the right shows the average rate of energy consumption, in kWh per day. The vampire experiment took place on 2nd October 2007. The combination of vampire-banishment with energy-saving-lightbulb installation reduced my electricity consumption from 4 kWh/d to 2 kWh/d.

Notes and further reading

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155 *Standby power consumption accounts for roughly 8% of residential electricity.* Source: International Energy Agency (2001).
For further reading on standby-power policies, see:
`www.iea.org/textbase/subjectqueries/standby.asp`.

23 Sustainable fossil fuels?

It is an inescapable reality that fossil fuels will continue to be an important part of the energy mix for decades to come.

UK government spokesperson, April 2008

Our present happy progressive condition is a thing of limited duration.

William Stanley Jevons, 1865

Figure 23.1. Coal being delivered to Kingsnorth power station (capacity 1940 MW) in 2005. Photos by Ian Boyle `www.simplonpc.co.uk`.

We explored in the last three chapters the main technologies and lifestyle changes for reducing power consumption. We found that we could halve the power consumption of transport (and de-fossilize it) by switching to electric vehicles. We found that we could shrink the power consumption of heating even more (and de-fossilize it) by insulating all buildings better and using electric heat pumps instead of fossil fuels. So yes, we can reduce consumption. But still, matching even this reduced consumption with power from Britain's own renewables looks very challenging (figure 18.7, p109). It's time to discuss non-renewable options for power production.

Take the known reserves of fossil fuels, which are overwhelmingly coal: 1600 Gt of coal. Share them equally between six billion people, and burn them "sustainably." What do we mean if we talk about using up a finite resource "sustainably"? Here's the arbitrary definition I'll use: the burn-rate is "sustainable" if the resources would last 1000 years. A ton of coal delivers 8000 kWh of chemical energy, so 1600 Gt of coal shared between 6 billion people over 1000 years works out to a power of 6 kWh per day per person. A standard coal power station would turn this chemical power into electricity with an efficiency of about 37% – that means about 2.2 kWh(e) per day per person. If we care about the climate, however, then presumably we would not use a standard power station. Rather, we would go for "clean coal," also known as "coal with carbon capture and storage" – an as-yet scarcely-implemented technology that sucks most of the carbon dioxide out of the chimney-flue gases and then shoves it down a hole in the ground. Cleaning up power station emissions in this way has a significant energy cost – it would reduce the delivered electricity by about 25%. So a "sustainable" use of known coal reserves would deliver only about 1.6 kWh(e) per day per person.

Coal: **6 kWh/d**

Figure 23.2. "Sustainable fossil fuels."

We can compare this "sustainable" coal-burning rate – 1.6 Gt per year – with the current global rate of coal consumption: 6.3 Gt per year, and rising.

What about the UK alone? Britain is estimated to have 7 Gt of coal left. OK, if we share 7 Gt between 60 million people, we get 100 tons per person. If we want a 1000-year solution, this corresponds to 2.5 kWh per

day per person. In a power station performing carbon capture and storage, this sustainable approach to UK coal would yield 0.7 kWh(e) per day per person.

Our conclusion is clear:

Clean coal is only a stop-gap.

If we do develop "clean coal" technology in order to reduce greenhouse gas emissions, we must be careful, while patting ourselves on the back, to do the accounting honestly. The coal-burning process releases greenhouse gases not only at the power station but also at the coal mine. Coal-mining tends to release methane, carbon monoxide, and carbon dioxide, both directly from the coal seams as they are exposed, and subsequently from discarded shales and mudstones; for an ordinary coal power station, these coal-mine emissions bump up the greenhouse gas footprint by about 2%, so for a "clean" coal power station, these emissions may have some impact on the accounts. There's a similar accounting problem with natural gas: if, say, 5% of the natural gas leaks out along the journey from hole in the ground to power station, then this accidental methane pollution is equivalent (in greenhouse effect) to a 40% boost in the carbon dioxide released at the power station.

Figure 23.3. A caterpillar grazing on old leaves. Photo by Peter Gunn.

New coal technologies

Stanford-based company `directcarbon.com` are developing the *Direct Carbon Fuel Cell*, which converts fuel and air directly to electricity and CO_2, without involving any water or steam turbines. They claim that this way of generating electricity from coal is twice as efficient as the standard power station.

When's the end of business as usual?

The economist Jevons did a simple calculation in 1865. People were discussing how long British coal would last. They tended to answer this question by dividing the estimated coal remaining by the rate of coal consumption, getting answers like "1000 years." But, Jevons said, consumption is *not* constant. It's been doubling every 20 years, and "progress" would have it continue to do so. So "reserves divided by consumption-rate" gives the wrong answer.

Instead, Jevons extrapolated the exponentially-growing consumption, calculating the time by which the total amount consumed would exceed the estimated reserves. This was a much shorter time. Jevons was not assuming that consumption would actually continue to grow at the same rate; rather he was making the point that growth was not sustainable. His calculation estimated for his British readership the inevitable limits

to their growth, and the short time remaining before those limits would become evident. Jevons made the bold prediction that the end of British "progress" would come within 100 years of 1865. Jevons was right. British coal production peaked in 1910, and by 1965 Britain was no longer a world superpower.

Let's repeat his calculation for the world as a whole. In 2006, the coal consumption rate was 6.3 Gt per year. Comparing this with reserves of 1600 Gt of coal, people often say "there's 250 years of coal left." But if we assume "business as usual" implies a growing consumption, we get a different answer. If the growth rate of coal consumption were to continue at 2% per year (which gives a reasonable fit to the data from 1930 to 2000), then all the coal would be gone in 2096. If the growth rate is 3.4% per year (the growth rate over the last decade), the end of business-as-usual is coming before 2072. Not 250 years, but 60!

If Jevons were here today, I am sure he would firmly predict that unless we steer ourselves on a course different from business as usual, there will, by 2050 or 2060, be an end to our happy progressive condition.

Notes and further reading

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157 *1000 years – my arbitrary definition of "sustainable."* As precedent for this sort of choice, Hansen et al. (2007) equate "more than 500 years" with "forever."

– *1 ton of coal equivalent = 29.3 GJ = 8000 kWh* of chemical energy. This figure does not include the energy costs of mining, transport, and carbon sequestration.

– *Carbon capture and storage* (CCS). There are several CCS technologies. Sucking the CO_2 from the flue gases is one; others gasify the coal and separate the CO_2 before combustion. See Metz et al. (2005). The first prototype coal plant with CCS was opened on 9th September 2008 by the Swedish company Vattenfall [5kpjk8].

– *UK coal.* In December 2005, the reserves and resources at *existing mines* were estimated to be 350 million tons. In November 2005, potential opencast reserves were estimated to be 620 million tons; and the underground coal gasification potential was estimated to be at least 7 billion tons. [yebuk8]

158 *Coal-mining tends to release greenhouse gases.* For information about methane release from coal-mining see www.epa.gov/cmop/, Jackson and Kershaw (1996), Thakur et al. (1996). Global emissions of methane from coal mining are about 400 Mt CO_2e per year. This corresponds to roughly 2% of the greenhouse gas emissions from burning the coal.

The average methane content in British coal seams is 4.7 m^3 per ton of coal (Jackson and Kershaw, 1996); this methane, if released to the atmosphere, has a global warming potential about 5% of that of the CO_2 from burning the coal.

158 *If 5% of the natural gas leaks, it's equivalent to a 40% boost in carbon dioxide.* Accidental methane pollution has nearly eight times as big a global-warming effect as the CO_2 pollution that would arise from burning the methane; eight times, not the standard "23 times," because "23 times" is the warming ratio between equal *masses* of methane and CO_2. Each ton of CH_4 turns into 2.75 tons of CO_2 if burned; if it leaks, it's equivalent to 23 tons of CO_2. And 23/2.75 is 8.4.

Further reading: World Energy Council [yhxf8b]

Further reading about underground coal gasification: [e2m9n]

24 Nuclear?

> *We made the mistake of lumping nuclear energy in with nuclear weapons, as if all things nuclear were evil. I think that's as big a mistake as if you lumped nuclear medicine in with nuclear weapons.*
>
> Patrick Moore,
> former Director of Greenpeace International

Nuclear power comes in two flavours. Nuclear *fission* is the flavour that we know how to use in power stations; fission uses uranium, an exceptionally heavy element, as fuel. Nuclear *fusion* is the flavour that we don't yet know how to implement in power stations; fusion would use light elements, especially hydrogen, as its fuel. Fission reactions split up heavy nuclei into medium-sized nuclei, releasing energy. Fusion reactions fuse light nuclei into medium-sized nuclei, releasing energy.

Both forms of nuclear power, fission and fusion, have an important property: the nuclear energy available per atom is roughly one million times bigger than the chemical energy per atom of typical fuels. This means that the amounts of fuel and waste that must be dealt with at a nuclear reactor can be up to one million times smaller than the amounts of fuel and waste at an equivalent fossil-fuel power station.

Let's try to personalize these ideas. The mass of the fossil fuels consumed by "the average British person" is about 16 kg per day (4 kg of coal, 4 kg of oil, and 8 kg of gas). That means that every single day, an amount of fossil fuels with the same weight as 28 pints of milk is extracted from a hole in the ground, transported, processed, and burned somewhere on your behalf. The average Brit's fossil fuel habit creates 11 tons per year of waste carbon dioxide; that's 30 kg per day. In the previous chapter we raised the idea of capturing waste carbon dioxide, compressing it into solid or liquid form, and transporting it somewhere for disposal. Imagine that one person was responsible for capturing and dealing with all their own carbon dioxide waste. 30 kg per day of carbon dioxide is a substantial rucksack-full every day – the same weight as 53 pints of milk!

In contrast, the amount of natural uranium required to provide the same amount of energy as 16 kg of fossil fuels, in a standard fission reactor, is 2 grams; and the resulting waste weighs one quarter of a gram. (This 2 g of uranium is not as small as one millionth of 16 kg per day, by the way, because today's reactors burn up less than 1% of the uranium.) To deliver 2 grams of uranium per day, the miners at the uranium mine would have to deal with perhaps 200 g of ore per day.

So the material streams flowing into and out of nuclear reactors are small, relative to fossil-fuel streams. "Small is beautiful," but the fact that the nuclear waste stream is small doesn't mean that it's not a problem; it's just a "beautifully small" problem.

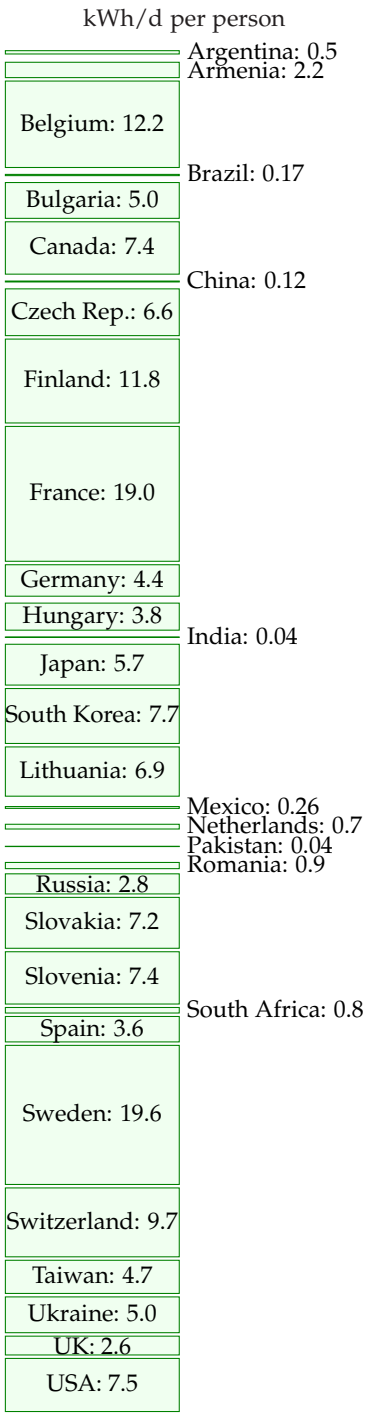


Figure 24.1. Electricity generated per capita from nuclear fission in 2007, in kWh per day per person, in each of the countries with nuclear power.

"Sustainable" power from nuclear fission

Figure 24.1 shows how much electricity was generated globally by nuclear power in 2007, broken down by country.

Could nuclear power be "sustainable"? Leaving aside for a moment the usual questions about safety and waste-disposal, a key question is whether humanity could live for generations on fission. How great are the world-wide supplies of uranium, and other fissionable fuels? Do we have only a few decades' worth of uranium, or do we have enough for millennia?

To estimate a "sustainable" power from uranium, I took the total recoverable uranium in the ground and in seawater, divided it fairly between 6 billion humans, and asked "how fast can we use this if it has to last 1000 years?"

Almost all the recoverable uranium is in the oceans, not in the ground: seawater contains 3.3 mg of uranium per m^3 of water, which adds up to 4.5 billion tons worldwide. I called the uranium in the ocean "recoverable" but this is a bit inaccurate – most ocean waters are quite inaccessible, and the ocean conveyor belt rolls round only once every 1000 years or so; and no-one has yet demonstrated uranium-extraction from seawater on an industrial scale. So we'll make separate estimates for two cases: first using only mined uranium, and second using ocean uranium too.

The uranium ore in the ground that's extractable at prices below $130 per kg of uranium is about one thousandth of this. If prices went above $130 per kg, phosphate deposits that contain uranium at low concentrations would become economic to mine. Recovery of uranium from phosphates is perfectly possible, and was done in America and Belgium before 1998. For the estimate of mined uranium, I'll add both the conventional uranium ore and the phosphates, to give a total resource of 27 million tons of uranium (table 24.2).

We'll consider two ways to use uranium in a reactor: (a) the widely-used *once-through method* gets energy mainly from the ^{235}U (which makes up just 0.7% of uranium), and discards the remaining ^{238}U; (b) *fast breeder reactors*, which are more expensive to build, convert the ^{238}U to fissionable plutonium-239 and obtain roughly 60 times as much energy from the uranium.

	million tons uranium
Australia	1.14
Kazakhstan	0.82
Canada	0.44
USA	0.34
South Africa	0.34
Namibia	0.28
Brazil	0.28
Russian Federation	0.17
Uzbekistan	0.12
World total (conventional reserves in the ground)	4.7
Phosphate deposits	22
Seawater	4 500

Table 24.2. Known recoverable resources of uranium. The top part of the table shows the "reasonable assured resources" and "inferred resources," at cost less than $130 per kg of uranium, as of 1 Jan 2005. These are the estimated resources in areas where exploration has taken place. There's also 1.3 million tons of depleted uranium sitting around in stockpiles, a by-product of previous uranium activities.

Figure 24.3. Workers push uranium slugs into the X-10 Graphite Reactor.

Once-through reactors, using uranium from the ground

A once-through **one-gigawatt** nuclear power station uses **162 tons per year of uranium**. So the known mineable resources of uranium, shared between 6 billion people, would last for 1000 years if we produced nuclear power at a rate of 0.55 kWh per day per person. This sustainable rate is the output of just 136 nuclear power stations, and is half of today's nuclear power production. It's very possible this is an underestimate of uranium's potential, since, as there is not yet a uranium shortage, there is no incentive for

exploration and little uranium exploration has been undertaken since the 1980s; so maybe more mineable uranium will be discovered. Indeed, one paper published in 1980 estimated that the low-grade uranium resource is more than 1000 times greater than the 27 million tons we just assumed.

Could our current once-through use of mined uranium be sustainable? It's hard to say, since there is such uncertainty about the result of future exploration. Certainly at today's rate of consumption, once-through reactors could keep going for hundreds of years. But if we wanted to crank up nuclear power 40-fold worldwide, in order to get off fossil fuels and to allow standards of living to rise, we might worry that once-through reactors are not a sustainable technology.

Figure 24.4. Three Mile Island nuclear power plant.

Fast breeder reactors, using uranium from the ground

Uranium can be used 60 times more efficiently in fast breeder reactors, which burn up all the uranium – both the ^{238}U and the ^{235}U (in contrast to the once-through reactors, which burn mainly ^{235}U). As long as we don't chuck away the spent fuel that is spat out by once-through reactors, this source of depleted uranium could be used too, so uranium that is put in once-through reactors need not be wasted. If we used all the mineable uranium (plus the depleted uranium stockpiles) in 60-times-more-efficient fast breeder reactors, the power would be 33 kWh per day per person. Attitudes to fast breeder reactors range from "this is a dangerous failed experimental technology whereof one should not speak" to "we can and should start building breeder reactors right away." I am not competent to comment on the risks of breeder technology, and I don't want to mix ethical assertions with factual assertions. My aim is just to help understand the numbers. The one ethical position I wish to push is "we should have a plan that adds up."

Figure 24.5. Dounreay Nuclear Power Development Establishment, whose primary purpose was the development of fast breeder reactor technology. Photo by John Mullen.

Once-through, using uranium from the oceans

The oceans' uranium, if completely extracted and used in once-through reactors, corresponds to a total energy of

$$\frac{4.5\,\text{billion tons per planet}}{162\,\text{tons uranium per GW-year}} = 28\,\text{million GW-years per planet.}$$

How fast could uranium be extracted from the oceans? The oceans circulate slowly: half of the water is in the Pacific Ocean, and deep Pacific waters circulate to the surface on the great ocean conveyor only every 1600 years. Let's imagine that 10% of the uranium is extracted over such a 1600-year period. That's an extraction rate of 280 000 tons per year. In once-through reactors, this would deliver power at a rate of

$$2.8\,\text{million GW-years} \;/\; 1600\,\text{years} = 1750\,\text{GW},$$

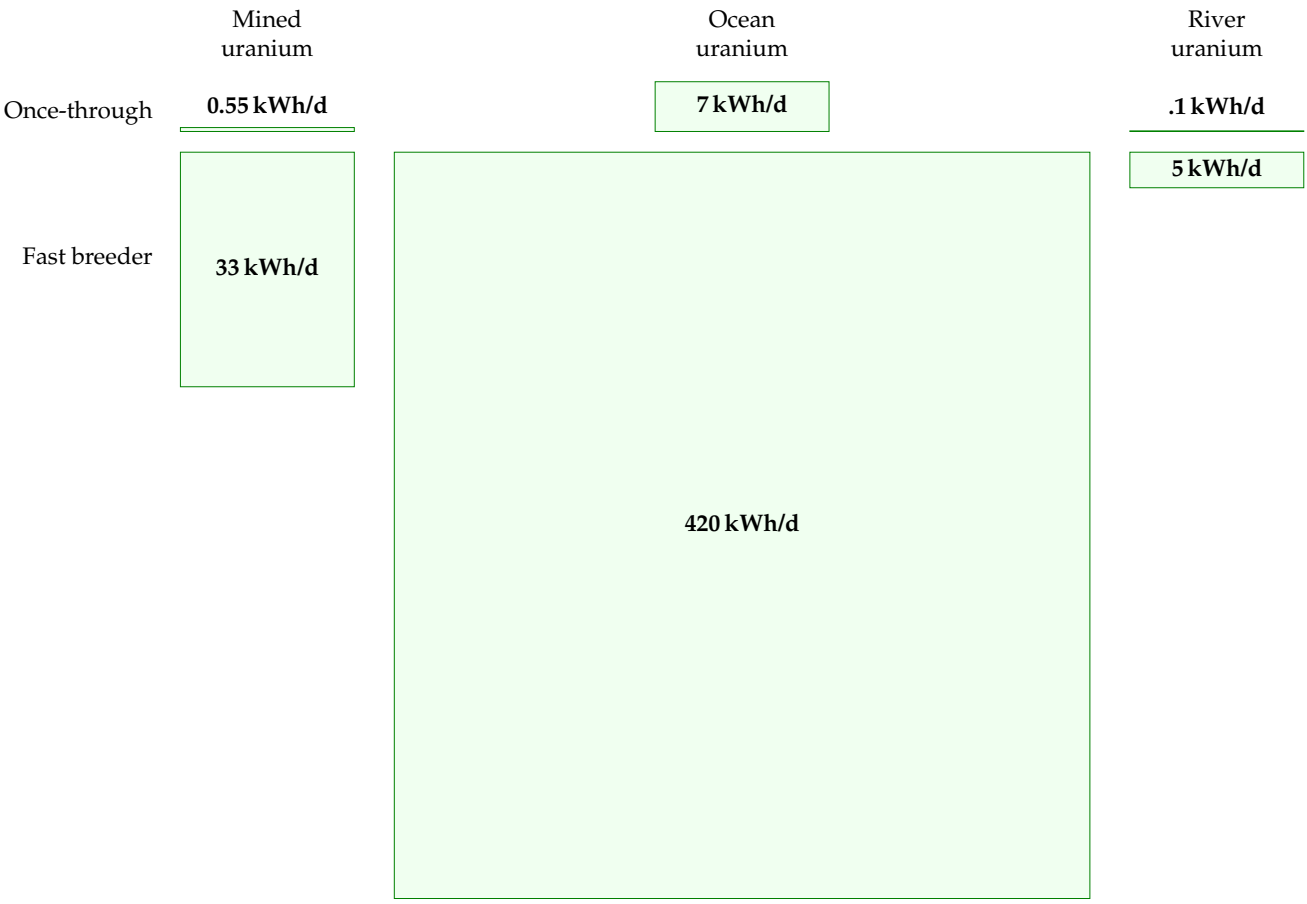


Figure 24.6. "Sustainable" power from uranium. For comparison, world nuclear power production today is 1.2 kWh/d per person. British nuclear power production used to be 4 kWh/d per person and is declining.

which, shared between 6 billion people, is 7 kWh per day per person. (There's currently 369 GW of nuclear reactors, so this figure corresponds to a 4-fold increase in nuclear power over today's levels.) I conclude that ocean extraction of uranium would turn today's once-through reactors into a "sustainable" option – assuming that the uranium reactors can cover the energy cost of the ocean extraction process.

Fast breeder reactors, using uranium from the oceans

If fast reactors are 60 times more efficient, the same extraction of ocean uranium could deliver 420 kWh per day per person. At last, a sustainable figure that beats current consumption! – but only with the joint help of two technologies that are respectively scarcely-developed and unfashionable: ocean extraction of uranium, and fast breeder reactors.

Using uranium from rivers

The uranium in the oceans is being topped up by rivers, which deliver uranium at a rate of 32 000 tons per year. If 10% of this influx were captured, it would provide enough fuel for 20 GW of once-through reactors, or 1200 GW of fast breeder reactors. The fast breeder reactors would deliver 5 kWh per day per person.

All these numbers are summarized in figure 24.6.

What about costs?

As usual in this book, my main calculations have paid little attention to economics. However, since the potential contribution of ocean-uranium-based power is one of the biggest in our "sustainable" production list, it seems appropriate to discuss whether this uranium-power figure is at all economically plausible.

Japanese researchers have found a technique for extracting uranium from seawater at a cost of $100–300 per kilogram of uranium, in comparison with a current cost of about $20/kg for uranium from ore. Because uranium contains so much more energy per ton than traditional fuels, this 5-fold or 15-fold increase in the cost of uranium would have little effect on the cost of nuclear power: nuclear power's price is dominated by the cost of power-station construction and decommissioning, not by the cost of the fuel. Even a price of $300/kg would increase the cost of nuclear energy by only about 0.3 p per kWh. The expense of uranium extraction could be reduced by combining it with another use of seawater – for example, power-station cooling.

We're not home yet: does the Japanese technique scale up? What is the energy cost of processing all the seawater? In the Japanese experiment, three cages full of adsorbent uranium-attracting material weighing 350 kg collected "more than 1 kg of yellow cake in 240 days;" this figure corresponds to about 1.6 kg per year. The cages had a cross-sectional area of 48 m^2. To power a once-through 1 GW nuclear power station, we need 160 000 kg per year, which is a production rate 100 000 times greater than the Japanese experiment's. If we simply scaled up the Japanese technique, which accumulated uranium passively from the sea, a power of 1 GW would thus need cages having a collecting area of 4.8 km^2 and containing a weight of 350 000 tons of adsorbent material – more than the weight of the steel in the reactor itself. To put these large numbers in human terms, if uranium were delivering, say, 22 kWh per day per person, each 1 GW reactor would be shared between 1 million people, each of whom needs 0.16 kg of uranium per year. So each person would require one tenth of the Japanese experimental facility, with a weight of 35 kg per person, and an area of 5 m^2 per person. The proposal that such uranium-extraction facilities should be created is thus similar in scale to proposals such as "every person should have 10 m^2 of solar panels" and "every person should have a

one-ton car and a dedicated parking place for it." A large investment, yes, but not absurdly off scale. And that was the calculation for once-through reactors. For fast breeder reactors, 60 times less uranium is required, so the mass per person of the uranium collector would be 0.5 kg.

Thorium

Thorium is a radioactive element similar to uranium. Formerly used to make gas mantles, it is about three times as abundant in the earth's crust as uranium. Soil commonly contains around 6 parts per million of thorium, and some minerals contain 12% thorium oxide. Seawater contains little thorium, because thorium oxide is insoluble. Thorium can be completely burned up in simple reactors (in contrast to standard uranium reactors which use only about 1% of natural uranium). Thorium is used in nuclear reactors in India. If uranium ore runs low, thorium will probably become the dominant nuclear fuel.

Thorium reactors deliver 3.6 billion kWh of heat per ton of thorium, which implies that a 1 GW reactor requires about 6 tons of thorium per year, assuming its generators are 40% efficient. Worldwide thorium resources are estimated to total about 6 million tons, four times more than the known reserves shown in table 24.7. As with the uranium resources, it seems plausible that these thorium resources are an underestimate, since thorium prospecting is not highly valued today. If we assume, as with uranium, that these resources are used up over 1000 years and shared equally among 6 billion people, we find that the "sustainable" power thus generated is 4 kWh/d per person.

An alternative nuclear reactor for thorium, the "energy amplifier" or "accelerator-driven system" proposed by Nobel laureate Carlo Rubbia and his colleagues would, they estimated, convert 6 million tons of thorium to 15 000 TWy of energy, or 60 kWh/d per person over 1000 years. Assuming conversion to electricity at 40% efficiency, this would deliver 24 kWh/d per person for 1000 years. And the waste from the energy amplifier would be much less radioactive too. They argue that, in due course, many times more thorium would be economically extractable than the current 6 million tons. If their suggestion – 300 times more – is correct, then thorium and the energy amplifier could offer 120 kWh/d per person for 60 000 years.

Country	Reserves (1000 tons)
Turkey	380
Australia	300
India	290
Norway	170
USA	160
Canada	100
South Africa	35
Brazil	16
Other countries	95
World total	1 580

Table 24.7. Known world thorium resources in monazite (economically extractable).

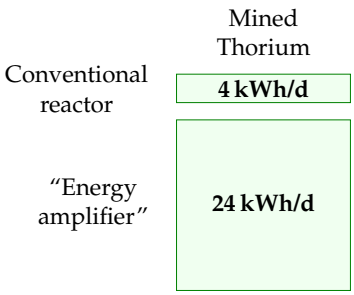


Figure 24.8. Thorium options.

Land use

Let's imagine that Britain decides it is serious about getting off fossil fuels, and creates a lot of new nuclear reactors, even though this may not be "sustainable." If we build enough reactors to make possible a significant decarbonization of transport and heating, can we fit the required nuclear reactors into Britain? The number we need to know is the power

per unit area of nuclear power stations, which is about 1000 W/m^2 (figure 24.10). Let's imagine generating 22 kWh per day per person of nuclear power – equivalent to 55 GW (roughly the same as France's nuclear power), which could be delivered by 55 nuclear power stations, each occupying one square kilometre. That's about 0.02% of the area of the country. Wind farms delivering the same average power would require 500 times as much land: 10% of the country. If the nuclear power stations were placed in pairs around the coast (length about 3000 km, at 5 km resolution), then there'd be two every 100 km. Thus while the area required is modest, the fraction of coastline gobbled by these power stations would be about 2% (2 kilometres in every 100).

Figure 24.9. Sizewell's power stations. Sizewell A, in the foreground, had a capacity of 420 MW, and was shut down at the end of 2006. Sizewell B, behind, has a capacity of 1.2 GW. Photo by William Connolley.

Economics of cleanup

What's the cost of cleaning up nuclear power sites? The nuclear decommissioning authority has an annual budget of £2 billion for the next 25 years. The nuclear industry sold everyone in the UK 4 kWh/d for about 25 years, so the nuclear decommissioning authority's cost is 2.3 p/kWh. That's a hefty subsidy – though not, it must be said, as hefty as the subsidy currently given to offshore wind (7 p/kWh).

Safety

The safety of nuclear operations in Britain remains a concern. The THORP reprocessing facility at Sellafield, built in 1994 at a cost of £1.8 billion, had a growing leak from a broken pipe from August 2004 to April 2005. Over eight months, the leak let *85 000 litres* of uranium-rich fluid flow into a sump which was equipped with safety systems that were designed to detect immediately any leak of as little as *15 litres*. But the leak went undetected because the operators hadn't completed the checks that ensured the safety systems were working; and the operators were in the habit of ignoring safety alarms anyway.

The safety system came with belt and braces. Independent of the failed safety alarms, routine safety-measurements of fluids in the sump should have detected the abnormal presence of uranium within one month of the start of the leak; but the operators often didn't bother taking these routine measurements, because they felt too busy; and when they *did* take measurements that detected the abnormal presence of uranium in the sump (on 28 August 2004, 26 November 2004, and 24 February 2005), no action was taken.

By April 2005, *22 tons* of uranium had leaked, but still none of the leak-detection systems detected the leak. The leak was finally detected by *accountancy*, when the bean-counters noticed that they were getting 10% less uranium out than their clients claimed they'd put in! Thank goodness this private company had a profit motive, hey? The criticism from the

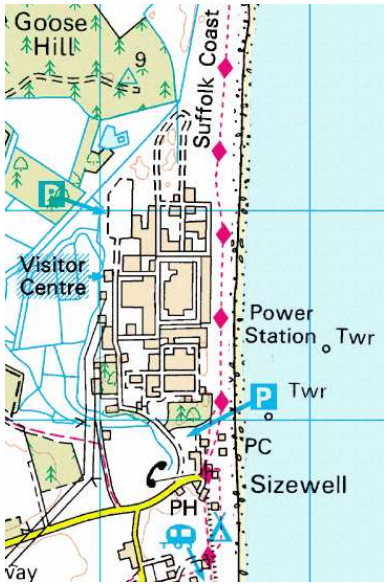


Figure 24.10. Sizewell occupies less than 1 km^2. The blue grid's spacing is 1 km. © Crown copyright; Ordnance Survey.

Chief Inspector of Nuclear Installations was withering: "The Plant was operated in a culture that seemed to allow instruments to operate in alarm mode rather than questioning the alarm and rectifying the relevant fault."

If we let private companies build new reactors, how can we ensure that higher safety standards are adhered to? I don't know.

At the same time, we must not let ourselves be swept off our feet in horror at the danger of nuclear power. Nuclear power is not infinitely dangerous. It's just dangerous, much as coal mines, petrol repositories, fossil-fuel burning and wind turbines are dangerous. Even if we have no guarantee against nuclear accidents in the future, I think the right way to assess nuclear is to compare it objectively with other sources of power. Coal power stations, for example, expose the public to nuclear radiation, because coal ash typically contains uranium. Indeed, according to a paper published in the journal *Science*, people in America living near coal-fired power stations are exposed to higher radiation doses than those living near nuclear power plants.

When quantifying the public risks of different power sources, we need a new unit. I'll go with "deaths per GWy (gigawatt-year)." Let me try to convey what it would mean if a power source had a death rate of 1 death per GWy. One gigawatt-year is the energy produced by a 1 GW power station, if it operates flat-out for one year. Britain's electricity consumption is roughly 45 GW, or, if you like, 45 gigawatt-years per year. So if we got our electricity from sources with a death rate of 1 death per GWy, that would mean the British electricity supply system was killing 45 people per year. For comparison, 3000 people die per year on Britain's roads. So, if you are *not* campaigning for the abolition of roads, you may deduce that "1 death per GWy" is a death rate that, while sad, you might be content to live with. Obviously, 0.1 deaths per GWy would be preferable, but it takes only a moment's reflection to realize that, sadly, fossil-fuel energy production must have a cost greater than 0.1 deaths per GWy – just think of disasters on oil rigs; helicopters lost at sea; pipeline fires; refinery explosions; and coal mine accidents: there are tens of fossil-chain fatalities per year in Britain.

So, let's discuss the actual death rates of a range of electricity sources. The death rates vary a lot from country to country. In China, for example, the death rate in coal mines, per ton of coal delivered, is 50 times that of most nations. Figure 24.11 shows numbers from studies by the Paul Scherrer Institute and by a European Union project called ExternE, which made comprehensive estimates of all the impacts of energy production. According to the EU figures, coal, lignite, and oil have the highest death rates, followed by peat and biomass-power, with death rates above 1 per GWy. Nuclear and wind are the best, with death rates below 0.2 per GWy. Hydroelectricity is the best of all according to the EU study, but comes out worst in the Paul Scherrer Institute's study, because the latter surveyed a different set of countries.

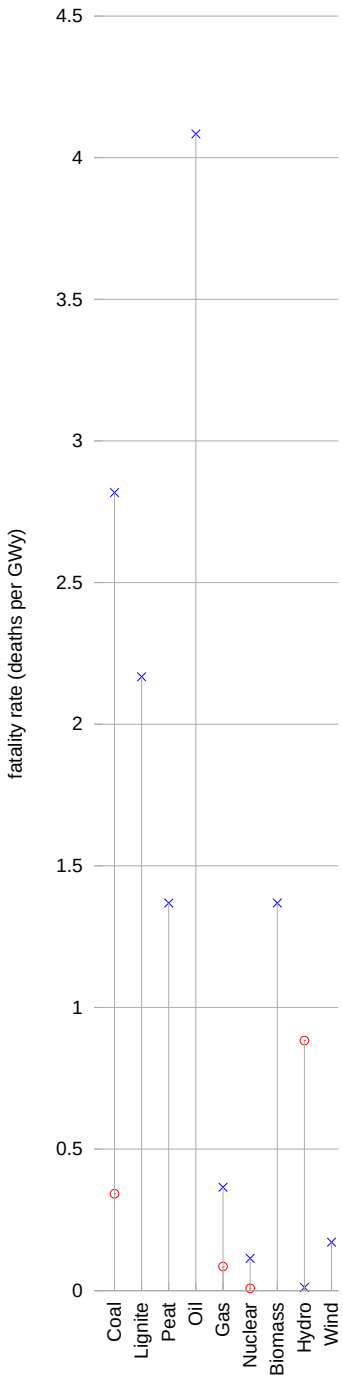


Figure 24.11. Death rates of electricity generation technologies. ×: European Union estimates by the ExternE project. ○: Paul Scherrer Institute.

Inherently safe nuclear power

Spurred on by worries about nuclear accidents, engineers have devised many new reactors with improved safety features. The GT-MHR power plant, for example, is claimed to be inherently safe; and, moreover it has a higher efficiency of conversion of heat to electricity than conventional nuclear plants [gt-mhr.ga.com].

Mythconceptions

Two widely-cited defects of nuclear power are construction costs, and waste. Let's examine some aspects of these issues.

Building a nuclear power station requires* huge *amounts of concrete and steel, materials whose creation involves* huge *CO_2 pollution.

The steel and concrete in a 1 GW nuclear power station have a carbon footprint of roughly 300 000 t CO_2.

Spreading this "huge" number over a 25-year reactor life we can express this contribution to the carbon intensity in the standard units (g CO_2 per kWh(e)),

$$\begin{aligned} \text{carbon intensity associated with construction} &= \frac{300 \times 10^9\,\text{g}}{10^6\,\text{kW(e)} \times 220\,000\,\text{h}} \\ &= 1.4\,\text{g/kWh(e)}, \end{aligned}$$

which is much smaller than the fossil-fuel benchmark of 400 g CO_2/kWh(e). The IPCC estimates that the *total* carbon intensity of nuclear power (including construction, fuel processing, and decommissioning) is less than 40 g CO_2/kWh(e) (Sims et al., 2007).

Please don't get me wrong: I'm not trying to be pro-nuclear. I'm just pro-arithmetic.

Isn't the waste from nuclear reactors a huge problem?

As we noted in the opening of this chapter, the volume of waste from nuclear reactors is relatively small. Whereas the ash from ten coal-fired power stations would have a mass of four million tons per year (having a volume of roughly 40 litres per person per year), the nuclear waste from Britain's ten nuclear power stations has a volume of just 0.84 litres per person per year – think of that as a bottle of wine per person per year (figure 24.13).

Most of this waste is low-level waste. 7% is intermediate-level waste, and just 3% of it – 25 ml per year – is high-level waste.

The high-level waste is the really nasty stuff. It's conventional to keep the high-level waste at the reactor for its first 40 years. It is stored in pools of water and cooled. After 40 years, the level of radioactivity has dropped 1000-fold. The level of radioactivity continues to fall; after 1000 years, the

Figure 24.12. Chernobyl power plant (top), and the abandoned town of Prypiat, which used to serve it (bottom). Photos by Nik Stanbridge.

radioactivity of the high-level waste is about the same as that of uranium ore. Thus waste storage engineers need to make a plan to secure high-level waste for about 1000 years.

Is this a difficult problem? 1000 years is certainly a long time compared with the lifetimes of governments and countries! But the volumes are so small, I feel nuclear waste is only a minor worry, compared with all the other forms of waste we are inflicting on future generations. At 25 ml per year, a lifetime's worth of high-level nuclear waste would amount to less than 2 litres. Even when we multiply by 60 million people, the lifetime volume of nuclear waste doesn't sound unmanageable: 105 000 cubic metres. That's the same volume as 35 olympic swimming pools. If this waste were put in a layer one metre deep, it would occupy just one tenth of a square kilometre.

There are already plenty of places that are off-limits to humans. I may not trespass in your garden. Nor should you in mine. We are neither of us welcome in Balmoral. "Keep out" signs are everywhere. Downing Street, Heathrow airport, military facilities, disused mines – they're all off limits. Is it impossible to imagine making another one-square-kilometre spot – perhaps deep underground – off limits for 1000 years?

Compare this 25 ml per year per person of high-level nuclear waste with the other traditional forms of waste we currently dump: municipal waste – 517 kg per year per person; hazardous waste – 83 kg per year per person.

People sometimes compare possible new nuclear waste with the nuclear waste we already have to deal with, thanks to our existing old reactors. Here are the numbers for the UK. The projected volume of "higher activity wastes" up to 2120, following decommissioning of existing nuclear facilities, is 478 000 m^3. Of this volume, 2% (about 10 000 m^3) will be the high level waste (1290 m^3) and spent fuel (8150 m^3) that together contain 92% of the activity. Building 10 new nuclear reactors (10 GW) would add another 31 900 m^3 of spent fuel to this total. That's the same volume as ten swimming pools.

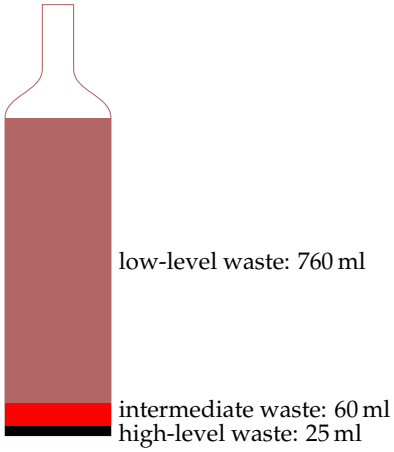


Figure 24.13. British nuclear waste, per person, per year, has a volume just a little larger than one wine bottle.

If we got lots and lots of power from nuclear fission or fusion, wouldn't this contribute to global warming, because of all the extra energy being released into the environment?

That's a fun question. And because we've carefully expressed everything in this book in a single set of units, it's quite easy to answer. First, let's recap the key numbers about global energy balance from p20: the average solar power absorbed by atmosphere, land, and oceans is 238 W/m^2; doubling the atmospheric CO_2 concentration would effectively increase the net heating by 4 W/m^2. This 1.7% increase in heating is believed to be bad news for climate. Variations in solar power during the 11-year solar cycle have a range of 0.25 W/m^2. So now let's assume that in 100 years or so, the world population is 10 billion, and everyone is living at a European stan-

dard of living, using 125 kWh per day derived from fossil sources, from nuclear power, or from mined geothermal power. The area of the earth per person would be 51 000 m^2. Dividing the power per person by the area per person, we find that the extra power contributed by human energy use would be 0.1 W/m^2. That's one fortieth of the 4 W/m^2 that we're currently fretting about, and a little smaller than the 0.25 W/m^2 effect of solar variations. So yes, under these assumptions, human power production would *just* show up as a contributor to global climate change.

I heard that nuclear power can't be built at a sufficient rate to make a useful contribution.

The difficulty of building nuclear power fast has been exaggerated with the help of a misleading presentation technique I call "the magic playing field." In this technique, two things appear to be compared, but the basis of the comparison is switched halfway through. The Guardian's environment editor, summarizing a report from the *Oxford Research Group*, wrote "For nuclear power to make any significant contribution to a reduction in global carbon emissions in the next two generations, the industry would have to construct nearly 3000 new reactors – or about one a week for 60 years. A civil nuclear construction and supply programme on this scale is a pipe dream, and completely unfeasible. The highest historic rate is 3.4 new reactors a year." 3000 sounds much bigger than 3.4, doesn't it! In this application of the "magic playing field" technique, there is a switch not only of timescale but also of *region*. While the first figure (3000 new reactors over 60 years) is the number required *for the whole planet*, the second figure (3.4 new reactors per year) is the maximum rate of building by a *single country* (France)!

A more honest presentation would have kept the comparison on a per-planet basis. France has 59 of the world's 429 operating nuclear reactors, so it's plausible that the highest rate of reactor building for the whole planet was something like ten times France's, that is, 34 new reactors per year. And the required rate (3000 new reactors over 60 years) is 50 new reactors per year. So the assertion that "civil nuclear construction on this scale is a pipe dream, and completely unfeasible" is poppycock. Yes, it's a big construction rate, but it's in the same ballpark as historical construction rates.

How reasonable is my assertion that the world's maximum historical construction rate must have been about 34 new nuclear reactors per year? Let's look at the data. Figure 24.14 shows the power of the world's nuclear fleet as a function of time, showing only the power stations still operational in 2007. The rate of new build was biggest in 1984, and had a value of (drum-roll please...) about 30 GW per year – about 30 1-GW reactors. So there!

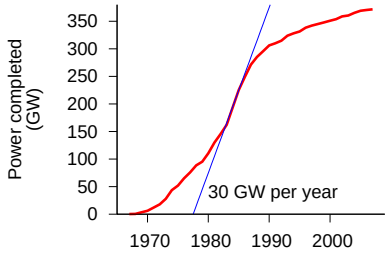


Figure 24.14. Graph of the total nuclear power in the world that was built since 1967 and that is still operational today. The world construction rate peaked at 30 GW of nuclear power per year in 1984.

What about nuclear fusion?

> *We say that we will put the sun into a box. The idea is pretty. The problem is, we don't know how to make the box.*
>
> Sébastien Balibar, Director of Research, CNRS

Fusion power is speculative and experimental. I think it is reckless to assume that the fusion problem *will* be cracked, but I'm happy to estimate how much power fusion could deliver, *if* the problem is cracked.

The two fusion reactions that are considered the most promising are:

the DT reaction, which fuses deuterium with tritium, making helium; and

the DD reaction, which fuses deuterium with deuterium.

Deuterium, a naturally occurring heavy isotope of hydrogen, can be obtained from seawater; tritium, a heavier isotope of hydrogen, isn't found in large quantities naturally (because it has a half-life of only 12 years) but it can be manufactured from lithium.

ITER is an international project to figure out how to make a steadily-working fusion reactor. The ITER prototype will use the DT reaction. DT is preferred over DD, because the DT reaction yields more energy and because it requires a temperature of "only" 100 million °C to get it going, whereas the DD reaction requires 300 million °C. (The maximum temperature in the sun is 15 million °C.)

Let's fantasize, and assume that the ITER project is successful. What sustainable power could fusion then deliver? Power stations using the DT reaction, fuelled by lithium, will run out of juice when the lithium runs out. Before that time, hopefully the second installment of the fantasy will have arrived: fusion reactors using deuterium alone.

I'll call these two fantasy energy sources "lithium fusion" and "deuterium fusion," naming them after the principal fuel we'd worry about in each case. Let's now estimate how much energy each of these sources could deliver.

Lithium fusion

World lithium reserves are estimated to be 9.5 million tons in ore deposits. If all these reserves were devoted to fusion over 1000 years, the power delivered would be 10 kWh/d per person.

There's another source for lithium: seawater, where lithium has a concentration of 0.17 ppm. To produce lithium at a rate of 100 million kg per year from seawater is estimated to have an energy requirement of 2.5 kWh(e) per gram of lithium. If the fusion reactors give back 2300 kWh(e) per gram of lithium, the power thus delivered would be 105 kWh/d per person (assuming 6 billion people). At this rate, the lithium in the oceans would last more than a million years.

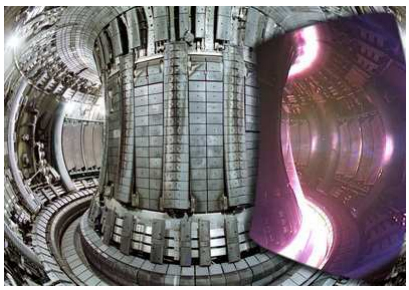


Figure 24.15. The inside of an experimental fusion reactor. Split image showing the JET vacuum vessel with a superimposed image of a JET plasma, taken with an ordinary TV camera. Photo: EFDA-JET.

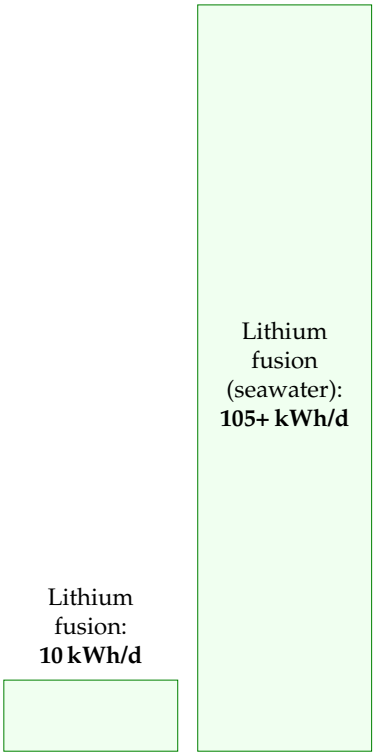


Figure 24.16. Lithium-based fusion, if used fairly and "sustainably," could match our current levels of consumption. Mined lithium would deliver 10 kWh/d per person for 1000 years; lithium extracted from seawater could deliver 105 kWh/d per person for over a million years.

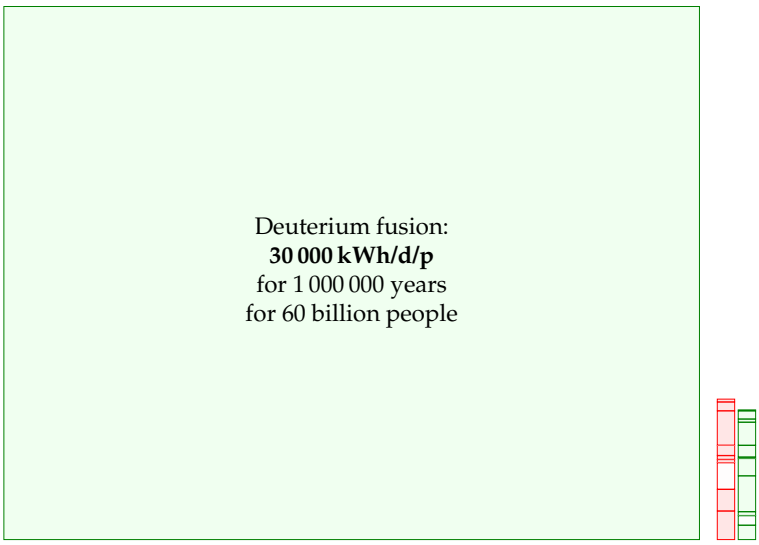


Figure 24.17. Deuterium-based fusion, if it is achievable, offers plentiful sustainable energy for millions of years. This diagram's scale is shrunk ten-fold in each dimension so as to fit fusion's potential contribution on the page. The red and green stacks from figure 18.1 are shown to the same scale, for comparison.

Deuterium fusion

If we imagine that scientists and engineers crack the problem of getting the DD reaction going, we have some very good news. There's 33 g of deuterium in every ton of water, and the energy that would be released from fusing just one gram of deuterium is a mind-boggling 100 000 kWh. Bearing in mind that the mass of the oceans is 230 million tons per person, we can deduce that there's enough deuterium to supply every person in a ten-fold increased world population with a power of 30 000 kWh per day (that's more than 100 times the average American consumption) for 1 million years (figure 24.17).

Notes and further reading

page no.

161 *Figure 24.1.* Source: World Nuclear Association [5qntkb]. The total capacity of operable nuclear reactors is 372 GW(e), using 65 000 tons of uranium per year. The USA has 99 GW, France 63.5 GW, Japan 47.6 GW, Russia 22 GW, Germany 20 GW, South Korea 17.5 GW, Ukraine 13 GW, Canada 12.6 GW, and UK 11 GW. In 2007 all the world's reactors generated 2608 TWh of electricity, which is an average of 300 GW, or 1.2 kWh per day per person.

162 *Fast breeder reactors obtain 60 times as much energy from the uranium.* Source: `www.world-nuclear.org/info/inf98.html`. Japan currently leads the development of fast breeder reactors.

– *A once-through one-gigawatt nuclear power station uses 162 tons per year of uranium.* Source: `www.world-nuclear.org/info/inf03.html`. A 1 GW(e) station with a thermal efficiency of 33% running at a load factor of 83% has the following upstream footprint: mining – 16 600 tons of 1%-uranium ore; milling – 191 t of uranium oxide (containing 162 t of natural uranium); enrichment and fuel fabrication – 22.4 t of uranium oxide (containing 20 t of enriched uranium). The enrichment requires 115 000 SWU; see p102 for the energy cost of SWU (separative work units).

163 *it's been estimated that the low-grade uranium resource is more than 1000 times greater than the 22 million* tons *we just assumed.* Deffeyes and MacGregor (1980) estimate that the resource of uranium in concentrations of 30 ppm or more is 3×10^{10} tons. (The average ore grade processed in South Africa in 1985 and 1990 was 150 ppm. Phosphates typically average 100 ppm.)
Here's what the World Nuclear Association said on the topic of uranium reserves in June 2008:
"From time to time concerns are raised that the known resources might be insufficient when judged as a multiple of present rate of use. But this is the Limits to Growth fallacy, ... which takes no account of the very limited nature of the knowledge we have at any time of what is actually in the Earth's crust. Our knowledge of geology is such that we can be confident that identified resources of metal minerals are a small fraction of what is there.
"Measured resources of uranium, the amount known to be economically recoverable from orebodies, are ... dependent on the intensity of past exploration effort, and are basically a statement about what is known rather than what is there in the Earth's crust.
"The world's present measured resources of uranium (5.5 Mt) ... are enough to last for over 80 years. This represents a higher level of assured resources than is normal for most minerals. Further exploration and higher prices will certainly, on the basis of present geological knowledge, yield further resources as present ones are used up."
"Economically rational players will only invest in finding these new reserves when they are most confident of gaining a return from them, which usually requires positive price messages caused by undersupply trends. If the economic system is working correctly and maximizing capital efficiency, there should never be more than a few decades of any resource commodity in reserves at any point in time."
[Exploration has a cost; exploring for uranium, for example, has had a cost of $1–$1.50 per kg of uranium ($3.4/MJ), which is 2% of the spot price of $78/kgU; in contrast, the finding costs of crude oil have averaged around $6/barrel ($1050/MJ) (12% of the spot price) over at least the past three decades.]
"Unlike the metals which have been in demand for centuries, society has barely begun to utilize uranium. There has been only one cycle of exploration-discovery-production, driven in large part by late 1970s price peaks.
"It is premature to speak about long-term uranium scarcity when the entire nuclear industry is so young that only one cycle of resource replenishment has been required." `www.world-nuclear.org/info/inf75.html`
Further reading: Herring (2004); Price and Blaise (2002); Cohen (1983).
The IPCC, citing the OECD, project that at the 2004 utilization levels, the uranium in conventional resources and phosphates would last 670 years in once-through reactors, 20 000 years in fast reactors with plutonium recycling, and 160 000 years in fast reactors recycling uranium and all actinides (Sims et al., 2007).

165 *Japanese researchers have found a technique for extracting uranium from seawater.* The price estimate of $100 per kg is from Seko et al. (2003) and [`y3wnzr`]; the estimate of $300 per kg is from OECD Nuclear Energy Agency (2006, p130). The uranium extraction technique involves dunking tissue in the ocean for a couple of months; the tissue is made of polymer fibres that are rendered sticky by irradiating them before they are dunked; the sticky fibres collect uranium to the tune of 2 g of uranium per kilogram of fibre.

– *The expense of uranium extraction could be reduced by combining it with another use of seawater – for example, power-station cooling.* The idea of a nuclear-powered island producing hydrogen was floated by C. Marchetti. Breeder reactors would be cooled by seawater and would extract uranium from the cooling water at a rate of 600 t uranium per 500 000 Mt of seawater.

166 *Thorium reactors deliver* 3.6×10^9 *kWh of heat per ton of thorium.* Source: `www.world-nuclear.org/info/inf62.html`. There remains scope for advancement in thorium reactors, so this figure could be bumped up in the future.

– *An alternative nuclear reactor for thorium, the "energy amplifier"...* See Rubbia et al. (1995), `web.ift.uib.no/~lillestol/Energy_Web/EA.html`, [`32t5zt`], [`2qr3yr`], [`ynk54y`].

– *World thorium resources in monazite.* source: US Geological Survey, Mineral Commodity Summaries, January 1999. [`yl7tkm`] Quoted in UIC Nuclear Issues Briefing Paper #67 November 2004.
"Other ore minerals with higher thorium contents, such as thorite, would be more likely sources if demand significantly increased."

[yju4a4] omits the figure for Turkey, which is found here: [yeyr7z].

167 *The nuclear industry sold everyone in the UK 4 kWh/d for about 25 years.* The total generated to 2006 was about 2200 TWh. Source: Stephen Salter's Energy Review for the Scottish National Party.

– *The nuclear decommissioning authority has an annual budget of £2 billion.* In fact, this clean-up budget seems to rise and rise. The latest figure for the total cost of decommissioning is £73 billion. news.bbc.co.uk/1/hi/uk/7215688.stm

168 *The criticism of the Chief Inspector of Nuclear Installations was withering...* (Weightman, 2007).

– *Nuclear power is not infinitely dangerous. It's just dangerous.* Further reading on risk: Kammen and Hassenzahl (1999).

– *People in America living near coal-fired power stations are exposed to higher radiation doses than those living near nuclear power plants.* Source: McBride et al. (1978). Uranium and thorium have concentrations of roughly 1 ppm and 2 ppm respectively in coal.
Further reading: gabe.web.psi.ch/research/ra/ra_res.html, www.physics.ohio-state.edu/~wilkins/energy/Companion/E20.12.pdf.xpdf.

– *Nuclear power and wind power have the lowest death rates.* See also Jones (1984). These death rates are from studies that are predicting the future. We can also look in the past.
In Britain, nuclear power has generated 200 GWy of electricity, and the nuclear industry has had 1 fatality, a worker who died at Chapelcross in 1978 [4f2ekz]. One death per 200 GWy is an impressively low death rate compared with the fossil fuel industry.
Worldwide, the nuclear-power historical death rate is hard to estimate. The Three Mile Island meltdown killed no-one, and the associated leaks are estimated to have perhaps killed one person in the time since the accident. The accident at Chernobyl first killed 62 who died directly from exposure, and 15 local people who died later of thyroid cancer; it's estimated that nearby, another 4000 died of cancer, and that worldwide, about 5000 people (among 7 million who were exposed to fallout) died of cancer because of Chernobyl (Williams and Baverstock, 2006); but these deaths are impossible to detect because cancers, many of them caused by natural nuclear radiation, already cause 25% of deaths in Europe.
One way to estimate a global death rate from nuclear power worldwide is to divide this estimate of Chernobyl's death-toll (9000 deaths) by the cumulative output of nuclear power from 1969 to 1996, which was 3685 GWy. This gives a death rate of 2.4 deaths per GWy.
As for deaths attributed to wind, Caithness Windfarm Information Forum www.caithnesswindfarms.co.uk list 49 fatalities worldwide from 1970 to 2007 (35 wind industry workers and 14 members of the public). In 2007, Paul Gipe listed 34 deaths total worldwide [www.wind-works.org/articles/BreathLife.html]. In the mid-1990s the mortality rate associated with wind power was 3.5 deaths per GWy. According to Paul Gipe, the worldwide mortality rate of wind power dropped to 1.3 deaths per GWy by the end of 2000.
So the historical death rates of both nuclear power and wind are higher than the predicted future death rates.

169 *The steel and concrete in a 1 GW nuclear power station have a carbon footprint of roughly 300 000 t CO_2.* A 1 GW nuclear power station contains 520 000 m^3 of concrete (1.2 million tons) and 67 000 tons of steel [2k8y7o]. Assuming 240 kg CO_2 per m^3 of concrete [3pvf4j], the concrete's footprint is around 100 000 t CO_2. From Blue Scope Steel [4r7zpg], the footprint of steel is about 2.5 tons of CO_2 per ton of steel. So the 67 000 tons of steel has a footprint of about 170 000 tons of CO_2.

170 *Nuclear waste discussion.* Sources: www.world-nuclear.org/info/inf04.html, [49hcnw], [3kduo7].
New nuclear waste compared with old. Committee on Radioactive Waste Management (2006).

172 *World lithium reserves are estimated as 9.5 million tons.* The main lithium sources are found in Bolivia (56.6%), Chile (31.4%) and the USA (4.3%). www.dnpm.gov.br

– *There's another source for lithium: seawater...* Several extraction techniques have been investigated (Steinberg and Dang, 1975; Tsuruta, 2005; Chitrakar et al., 2001).

– *Fusion power from lithium reserves.*
The energy density of natural lithium is about 7500 kWh per gram (Ongena and Van Oost, 2006). There's considerable variation among the estimates of how efficiently fusion reactors would turn this into electricity, ranging from 310 kWh(e)/g (Eckhartt, 1995) to 3400 kWh(e)/g of natural lithium (Steinberg and Dang, 1975). I've assumed 2300 kWh(e)/g, based on this widely quoted summary figure: "A 1 GW fusion plant will use about 100 kg of deuterium and 3 tons of natural lithium per year, generating about 7 billion kWh." [69vt8r], [6oby22], [631l1p].

Further reading about fission: Hodgson (1999), Nuttall (2004), Rogner (2000), Williams (2000). Uranium Information Center – www.uic.com.au. www.world-nuclear.org, [wnchw].
On costs: Zaleski (2005).
On waste repositories: [shrln].
On breeder reactors and thorium: www.energyfromthorium.com.

Further reading about fusion: www.fusion.org.uk, www.askmar.com/Fusion.html.

25 *Living on other countries' renewables?*

Whether the Mediterranean becomes an area of cooperation or confrontation in the 21st century will be of strategic importance to our common security.

Joschka Fischer, German Foreign Minister, February 2004

We've found that it's hard to get off fossil fuels by living on our own renewables. Nuclear has its problems too. So what else can we do? Well, how about living on someone else's renewables? (Not that we have any entitlement to someone else's renewables, of course, but perhaps they might be interested in selling them to us.)

Most of the resources for living sustainably are related to land area: if you want to use solar panels, you need land to put them on; if you want to grow crops, you need land again. Jared Diamond, in his book *Collapse*, observes that, while many factors contribute to the collapse of civilizations, a common feature of all collapses is that the human population density became too great.

Places like Britain and Europe are in a pickle because they have large population densities, and all the available renewables are diffuse – they have small power density (table 25.1). When looking for help, we should look to countries that have three things: *a*) low population density; *b*) large area; and *c*) a renewable power supply with high power density.

Power per unit land or water area	
Wind	2 W/m^2
Offshore wind	3 W/m^2
Tidal pools	3 W/m^2
Tidal stream	6 W/m^2
Solar PV panels	5–20 W/m^2
Plants	0.5 W/m^2
Rain-water (highlands)	0.24 W/m^2
Hydroelectric facility	11 W/m^2
Solar chimney	0.1 W/m^2
Concentrating solar power (desert)	**15** W/m^2

Table 25.1. Renewable facilities have to be country-sized because all renewables are so diffuse.

Region	Population	Area (km^2)	Density (persons per km^2)	Area per person (m^2)
Libya	5 760 000	1 750 000	3	305 000
Kazakhstan	15 100 000	2 710 000	6	178 000
Saudi Arabia	26 400 000	1 960 000	13	74 200
Algeria	32 500 000	2 380 000	14	73 200
Sudan	40 100 000	2 500 000	16	62 300
World	6 440 000 000	148 000 000	43	23 100
Scotland	5 050 000	78 700	64	15 500
European Union	496 000 000	4 330 000	115	8 720
Wales	2 910 000	20 700	140	7 110
United Kingdom	59 500 000	244 000	243	4 110
England	49 600 000	130 000	380	2 630

Table 25.2. Some regions, ordered from small to large population density. See p338 for more population densities.

Table 25.2 highlights some countries that fit the bill. Libya's population density, for example, is 70 times smaller than Britain's, and its area is 7 times bigger. Other large, area-rich, countries are Kazakhstan, Saudi Arabia, Algeria, and Sudan.

In all these countries, I think the most promising renewable is solar power, *concentrating solar power* in particular, which uses mirrors or lenses to focus sunlight. Concentrating solar power stations come in several flavours, arranging their moving mirrors in various geometries, and putting various power conversion technologies at the focus – Stirling engines, pressurized water, or molten salt, for example – but they all deliver fairly similar average powers per unit area, in the ballpark of 15 W/m^2.

Figure 25.3. Stirling dish engine. These beautiful concentrators deliver a power per unit land area of 14 W/m^2. Photo courtesy of Stirling Energy Systems. `www.stirlingenergy.com`

A technology that adds up

"All the world's power could be provided by a square 100 km by 100 km in the Sahara." Is this true? Concentrating solar power in deserts delivers an average power per unit land area of roughly 15 W/m^2. So, allowing no space for anything else in such a square, the power delivered would be 150 GW. This is *not* the same as current world power consumption. It's not even near current world *electricity* consumption, which is 2000 GW. World power consumption today is 15 000 GW. So the correct statement about power from the Sahara is that today's consumption could be provided by a *1000 km by 1000 km* square in the desert, completely filled with concentrating solar power. That's four times the area of the UK. And if we are interested in living in an equitable world, we should presumably aim to supply more than *today's* consumption. To supply every person in the world with an average European's power consumption (125 kWh/d), the area required would be *two* 1000 km by 1000 km squares in the desert.

Fortunately, the Sahara is not the only desert, so maybe it's more relevant to chop the world into smaller regions, and ask what area is needed in each region's local desert. So, focusing on Europe, "what area is required in the North Sahara to supply *everyone in Europe and North Africa* with an average European's power consumption? Taking the population of Europe and North Africa to be 1 billion, the area required drops to 340 000 km^2, which corresponds to a square **600 km by 600 km**. This area is equal to one Germany, to 1.4 United Kingdoms, or to **16 Waleses**.

The UK's share of this 16-Wales area would be one Wales: a 145 km by 145 km square in the Sahara would provide all the UK's current primary energy consumption. These squares are shown in figure 25.5. Notice that while the yellow square may look "little" compared with Africa, it does have the same area as Germany.

Figure 25.4. Andasol – a "100 MW" solar power station under construction in Spain. Excess thermal energy produced during the day will be stored in liquid salt tanks for up to seven hours, allowing a continuous and stable supply of electric power to the grid. The power station is predicted to produce 350 GWh per year (40 MW). The parabolic troughs occupy 400 hectares, so the power per unit land area will be 10 W/m^2. Upper photo: ABB. Lower photo: IEA SolarPACES.

The DESERTEC plan

An organization called DESERTEC [`www.desertec.org`] is promoting a plan to use concentrating solar power in sunny Mediterranean countries, and high-voltage direct-current (HVDC) transmission lines (figure 25.7) to deliver the power to cloudier northern parts. HVDC technology has been in use since 1954 to transmit power both through overhead lines and through

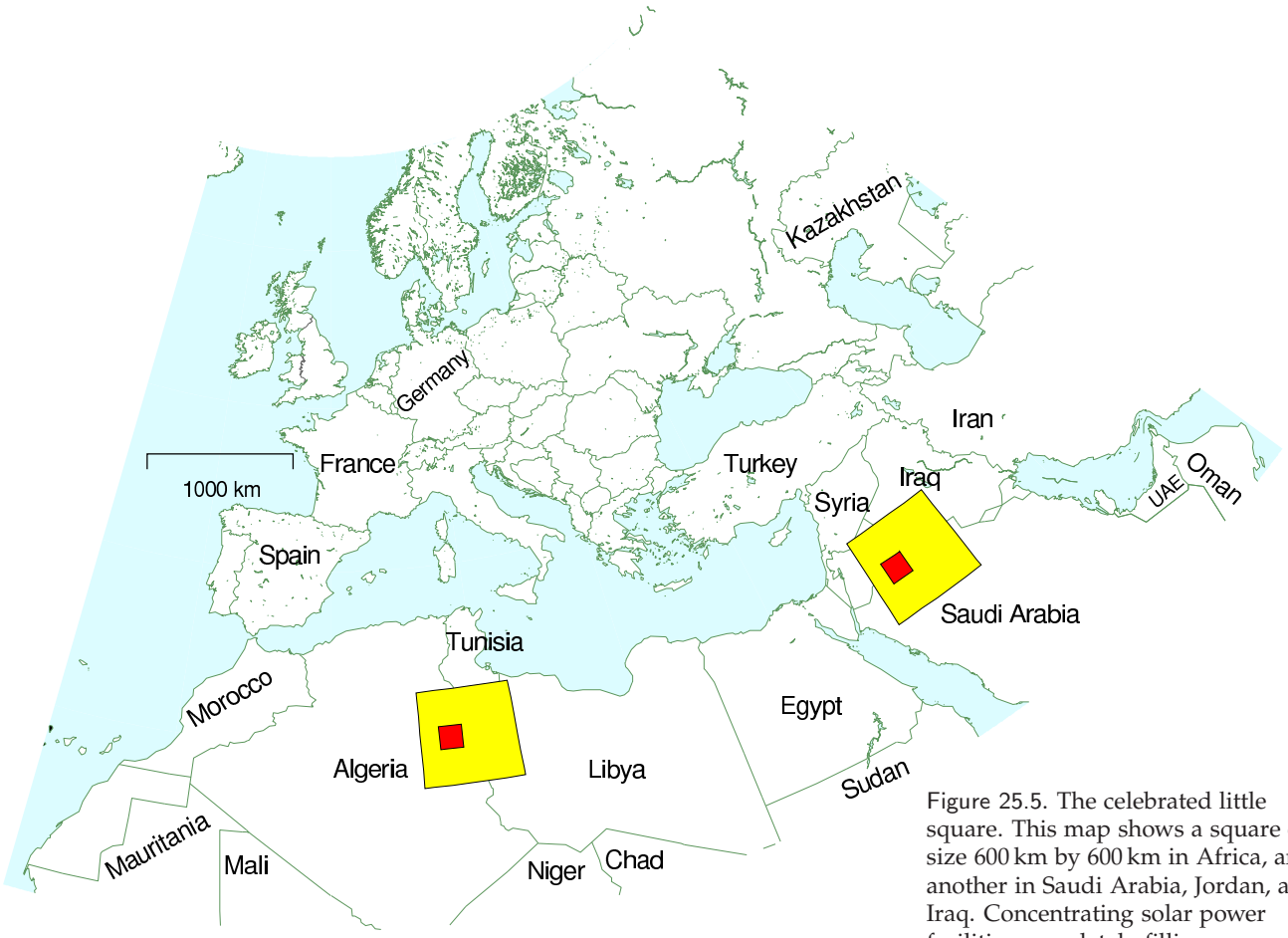


Figure 25.5. The celebrated little square. This map shows a square of size 600 km by 600 km in Africa, and another in Saudi Arabia, Jordan, and Iraq. Concentrating solar power facilities completely filling one such square would provide enough power to give 1 billion people the average European's consumption of 125 kWh/d. The area of one square is the same as the area of Germany, and 16 times the area of Wales. Within each big square is a smaller 145 km by 145 km square showing the area required in the Sahara – one Wales – to supply all British power consumption.

submarine cables (such as the interconnector between France and England). It is already used to transmit electricity over 1000-km distances in South Africa, China, America, Canada, Brazil, and Congo. A typical 500 kV line can transmit a power of 2 GW. A pair of HVDC lines in Brazil transmits 6.3 GW.

HVDC is preferred over traditional high-voltage AC lines because less physical hardware is needed, less land area is needed, and the power losses of HVDC are smaller. The power losses on a 3500 km-long HVDC line, including conversion from AC to DC and back, would be about 15%. A further advantage of HVDC systems is that they help stabilize the electricity networks to which they are connected.

In the DESERTEC plans, the prime areas to exploit are coastal areas, because concentrating solar power stations that are near to the sea can deliver desalinated water as a by-product – valuable for human use, and for agriculture.

Table 25.6 shows DESERTEC's estimates of the potential power that

Country	Economic potential (TWh/y)	Coastal potential (TWh/y)
Algeria	169 000	60
Libya	140 000	500
Saudi Arabia	125 000	2 000
Egypt	74 000	500
Iraq	29 000	60
Morocco	20 000	300
Oman	19 000	500
Syria	10 000	0
Tunisia	9 200	350
Jordan	6 400	0
Yemen	5 100	390
Israel	3 100	1
UAE	2 000	540
Kuwait	1 500	130
Spain	1 300	70
Qatar	800	320
Portugal	140	7
Turkey	130	12
Total	620 000 (70 000 GW)	6 000 (650 GW)

Table 25.6. Solar power potential in countries around and near to Europe. The "economic potential" is the power that could be generated in suitable places where the direct normal irradiance is more than 2000 kWh/m^2/y.
The "coastal potential" is the power that could be generated within 20 m (vertical) of sea level; such power is especially promising because of the potential combination with desalination.
For comparison, the total power required to give 125 kWh per day to 1 billion people is 46 000 TWh/y (5 200 GW). 6000 TWh/y (650 GW) is 16 kWh per day per person for 1 billion people.

could be produced in countries in Europe and North Africa. The "economic potential" adds up to more than enough to supply 125 kWh per day to 1 billion people. The total "coastal potential" is enough to supply 16 kWh per day per person to 1 billion people.

Let's try to convey on a map what a realistic plan could look like. Imagine making solar facilities each having an area of 1500 km^2 – that's roughly the size of London. (Greater London has an area of 1580 km^2; the M25 orbital motorway around London encloses an area of 2300 km^2.) Let's call each facility a *blob*. Imagine that in each of these blobs, half the area is devoted to concentrating power stations with an average power density of 15 W/m^2, leaving space around for agriculture, buildings, railways, roads, pipelines, and cables. Allowing for 10% transmission loss between the blob and the consumer, each of these blobs generates an average power of 10 GW. Figure 25.8 shows some blobs to scale on a map. To give a sense of the scale of these blobs I've dropped a few in Britain too. *Four* of these blobs would have an output roughly equal to Britain's total electricity consumption (16 kWh/d per person for 60 million people). *Sixty-five* blobs would provide all one billion people in Europe and North Africa with 16 kWh/d per person. Figure 25.8 shows 68 blobs in the desert.

Figure 25.7. Laying a high-voltage DC link between Finland and Estonia. A pair of these cables transmit a power of 350 MW. Photo: ABB.

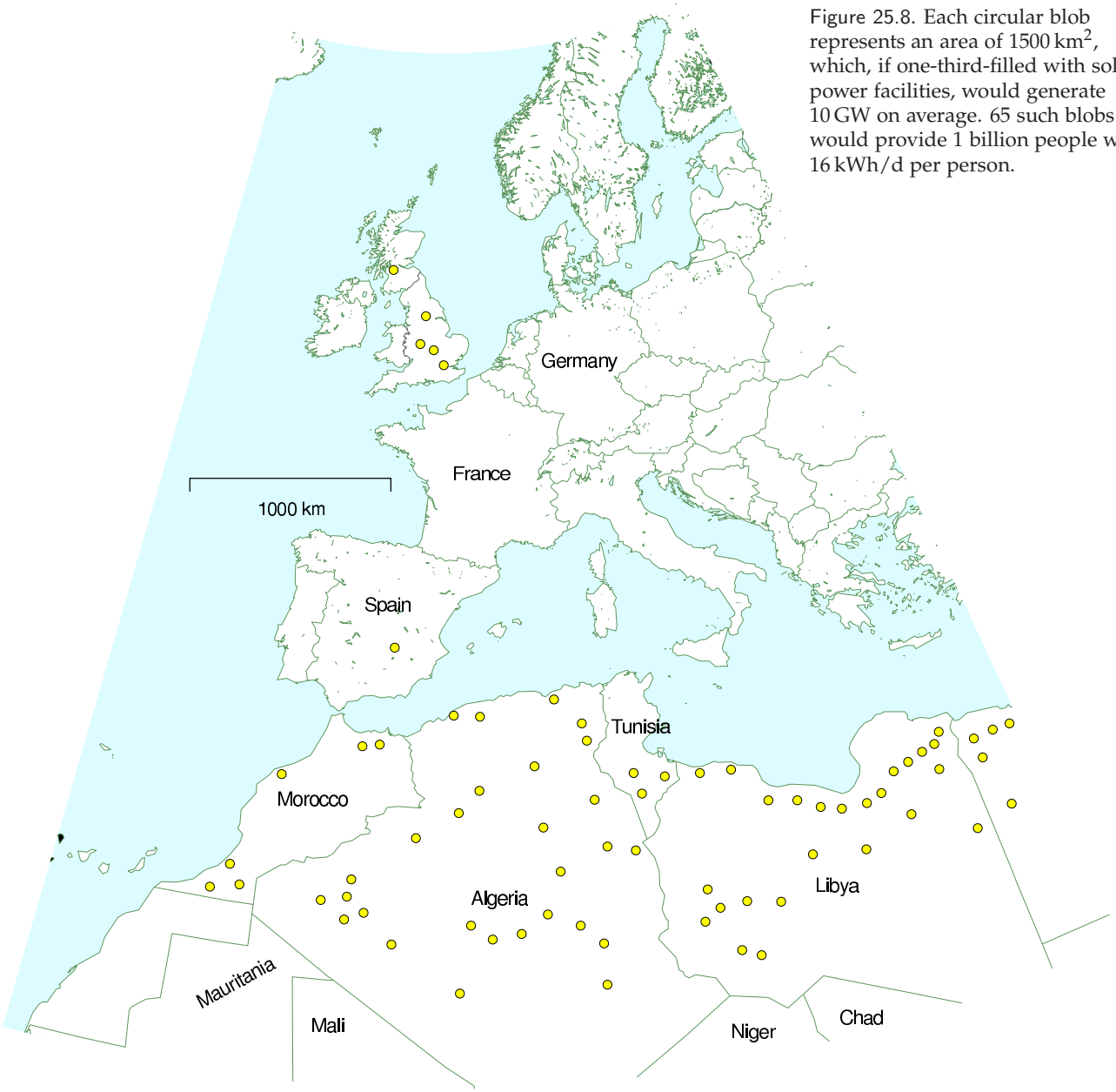


Figure 25.8. Each circular blob represents an area of 1500 km^2, which, if one-third-filled with solar power facilities, would generate 10 GW on average. 65 such blobs would provide 1 billion people with 16 kWh/d per person.

Concentrating photovoltaics

An alternative to concentrating thermal solar power in deserts is large-scale concentrating photovoltaic systems. To make these, we plop a high-quality electricity-producing solar cell at the focus of cheap lenses or mirrors. Faiman et al. (2007) say that "solar, in its concentrator photovoltaics variety, can be completely cost-competitive with fossil fuel [in desert states such as California, Arizona, New Mexico, and Texas] without the need for any kind of subsidy."

According to manufacturers Amonix, this form of concentrating solar power would have an average power per unit land area of 18 W/m^2.

Another way to get a feel for required hardware is to personalize. One of the "25 kW" (peak) collectors shown in figure 25.9 generates on average about 138 kWh per day; the American lifestyle currently uses 250 kWh per day per person. So to get the USA off fossil fuels using solar power, we need roughly two of these 15 m × 15 m collectors per person.

Figure 25.9. A 25 kW (peak) concentrator photovoltaic collector produced by Californian company Amonix. Its 225 m^2 aperture contains 5760 Fresnel lenses with optical concentration ×260, each of which illuminates a 25%-efficient silicon cell. One such collector, in an appropriate desert location, generates 138 kWh per day – enough to cover the energy consumption of half an American. Note the human providing a scale. Photo by David Faiman.

Queries

I'm confused! In Chapter 6, you said that the best photovoltaic panels deliver 20 W/m^2 on average, in a place with British sunniness. Presumably in the desert the same panels would deliver 40 W/m^2. So how come the concentrating solar power stations deliver only 15–20 W/m^2? Surely concentrating power should be even better than plain flat panels?

Good question. The short answer is no. Concentrating solar power does not achieve a better power per unit land area than flat panels. The concentrating contraption has to track the sun, otherwise the sunlight won't be focused right; once you start packing land with sun-tracking contraptions, you have to leave gaps between them; lots of sunlight falls through the gaps and is lost. The reason that people nevertheless make concentrating solar power systems is that, today, flat photovoltaic panels are very expensive, and concentrating systems are cheaper. The concentrating people's goal is not to make systems with big power per unit land area. Land area is cheap (they assume). The goal is to deliver big power per dollar.

But if flat panels have bigger power density, why don't you describe covering the Sahara desert with* them*?

Because I am trying to discuss practical options for large-scale sustainable power production for Europe and North Africa by 2050. My guess is that by 2050, mirrors will still be cheaper than photovoltaic panels, so concentrating solar power is the technology on which we should focus.

What about solar chimneys?

A solar chimney or solar updraft tower uses solar power in a very simple way. A huge chimney is built at the centre of an area covered by a transparent roof made of glass or plastic; because hot air rises, hot air created

in this greenhouse-like heat-collector whooshes up the chimney, drawing in cooler air from the perimeter of the heat-collector. Power is extracted from the air-flow by turbines at the base of the chimney. Solar chimneys are fairly simple to build, but they don't deliver a very impressive power per unit area. A pilot plant in Manzanares, Spain operated for seven years between 1982 and 1989. The chimney had a height of 195 m and a diameter of 10 m; the collector had a diameter of 240 m, and its roof had 6000 m^2 of glass and 40 000 m^2 of transparent plastic. It generated 44 MWh per year, which corresponds to a power per unit area of 0.1 W/m^2. Theoretically, the bigger the collector and the taller the chimney, the bigger the power density of a solar chimney becomes. The engineers behind Manzanares reckon that, at a site with a solar radiation of 2300 kWh/m^2 per year (262 W/m^2), a 1000 m-high tower surrounded by a 7 km-diameter collector could generate 680 GWh per year, an average power of 78 MW. That's a power per unit area of about 1.6 W/m^2, which is similar to the power per unit area of windfarms in Britain, and one tenth of the power per unit area I said concentrating solar power stations would deliver. It's claimed that solar chimneys could generate electricity at a price similar to that of conventional power stations. I suggest that countries that have enough land and sunshine to spare should host a big bake-off contest between solar chimneys and concentrating solar power, to be funded by oil-producing and oil-consuming countries.

Figure 25.10. The Manzanares prototype solar chimney. Photos from `solarmillennium.de`.

What about getting power from Iceland, where geothermal power and hydroelectricity are so plentiful?

Indeed, Iceland already effectively exports energy by powering industries that make energy-intensive products. Iceland produces nearly one ton of aluminium per citizen per year, for example! So from Iceland's point of view, there are great profits to be made. But can Iceland save Europe? I would be surprised if Iceland's power production could be scaled up enough to make sizeable electricity exports even to Britain alone. As a benchmark, let's compare with the England–France Interconnector, which can deliver up to 2 GW across the English Channel. That maximum power is equivalent to 0.8 kWh per day per person in the UK, roughly 5% of British average electricity consumption. Iceland's average geothermal electricity generation is just 0.3 GW, which is less than 1% of Britain's average electricity consumption. Iceland's average electricity production is 1.1 GW. So to create a link sending power equal to the capacity of the French interconnector, Iceland would have to *triple* its electricity production. To provide us with 4 kWh per day per person (roughly what Britain gets from its own nuclear power stations), Iceland's electricity production would have to increase *ten-fold*. It is probably a good idea to build interconnectors to Iceland, but don't expect them to deliver more than a small contribution.

Figure 25.11. More geothermal power in Iceland. Photo by Rosie Ward.

Notes and further reading

page no.

178 *Concentrating solar power in deserts delivers an average power per unit area of roughly 15 W/m^2.* My sources for this number are two companies making concentrating solar power for deserts.

`www.stirlingenergy.com` says one of its dishes with a 25 kW Stirling engine at its focus can generate 60 000 kWh/y in a favourable desert location. They could be packed at a concentration of one dish per 500 m^2. That's an average power of 14 W/m^2. They say that solar dish Stirling makes the best use of land area, in terms of energy delivered.

`www.ausra.com` uses flat mirrors to heat water to 285 °C and drive a steam turbine. The heated, pressurized water can be stored in deep metal-lined caverns to allow power generation at night. Describing a "240 MW(e)" plant proposed for Australia (Mills and Lièvre, 2004), the designers claim that 3.5 km^2 of mirrors would deliver 1.2 TWh(e); that's 38 W/m^2 of mirror. To find the power per unit land area, we need to allow for the gaps between the mirrors. Ausra say they need a 153 km by 153 km square in the desert to supply all US electric power (Mills and Morgan, 2008). Total US electricity is 3600 TWh/y, so they are claiming a power per unit land area of 18 W/m^2. This technology goes by the name *compact linear fresnel reflector* (Mills and Morrison, 2000; Mills et al., 2004; Mills and Morgan, 2008). Incidentally, rather than "concentrating solar power," the company Ausra prefers to use the term *solar thermal electricity* (STE); they emphasize the benefits of thermal storage, in contrast to concentrating photovoltaics, which don't come with a natural storage option.

Trieb and Knies (2004), who are strong proponents of concentrating solar power, project that the alternative concentrating solar power technologies would have powers per unit land area in the following ranges: parabolic troughs, 14–19 W/m^2; linear fresnel collector, 19–28 W/m^2; tower with heliostats, 9–14 W/m^2; stirling dish, 9–14 W/m^2.

There are three European demonstration plants for concentrating solar power. Andasol – using parabolic troughs; Solúcar PS10, a tower near Seville; and Solartres, a tower using molten salt for heat storage. The Andasol parabolic-trough system shown in figure 25.4 is predicted to deliver 10 W/m^2. Solúcar's "11 MW" solar tower has 624 mirrors, each 121 m^2. The mirrors concentrate sunlight to a radiation density of up to 650 kW/m^2. The receiver receives a peak power of 55 MW. The power station can store 20 MWh of thermal energy, allowing it to keep going during 50 minutes of cloudiness. It was expected to generate 24.2 GWh of electricity per year, and it occupies 55 hectares. That's an average power per unit land area of 5 W/m^2. (Source: Abengoa Annual Report 2003.) Solartres will occupy 142 hectares and is expected to produce 96.4 GWh per year; that's a power density of 8 W/m^2. Andasol and Solartres will both use some natural gas in normal operation.

179 *HVDC is already used to transmit electricity over 1000-km distances in South Africa, China, America, Canada, Brazil, and Congo.* Sources: Asplund (2004), Bahrman and Johnson (2007). Further reading on HVDC: Carlsson (2002).

Figure 25.12. Two engineers assembling an eSolar concentrating power station using heliostats (mirrors that rotate and tip to follow the sun). `esolar.com` make medium-scale power stations: a 33 MW (peak) power unit on a 64 hectare site. That's 51 W/m^2 peak, so I'd guess that in a typical desert location they would deliver about one quarter of that: 13 W/m^2.

Figure 25.13. A high-voltage DC power system in China. Photo: ABB.

179 *Losses on a 3500 km-long HVDC line, including conversion from AC to DC and back, would be about 15%.* Sources: Trieb and Knies (2004); van Voorthuysen (2008).

182 *According to Amonix, concentrating photovoltaics would have an average power per unit land area of 18 W/m^2.* The assumptions of `www.amonix.com` are: the lens transmits 85% of the light; 32% cell efficiency; 25% collector efficiency; and 10% further loss due to shading. Aperture/land ratio of 1/3. Normal direct irradiance: 2222 kWh/m^2/year. They expect each kW of peak capacity to deliver 2000 kWh/y (an average of 0.23 kW). A plant of 1 GW peak capacity would occupy 12 km^2 of land and deliver 2000 GWh per year. That's 18 W/m^2.

– *Solar chimneys.* Sources: Schlaich J (2001); Schlaich et al. (2005); Dennis (2006), `www.enviromission.com.au`, `www.solarairpower.com`.

183 *Iceland's average geothermal electricity generation is just 0.3 GW. Iceland's average electricity production is 1.1 GW.* These are the statistics for 2006: 7.3 TWh of hydroelectricity and 2.6 TWh of geothermal electricity, with capacities of 1.16 GW and 0.42 GW, respectively. Source: Orkustofnun National Energy Authority [`www.os.is/page/energystatistics`].

Further reading: European Commission (2007), German Aerospace Center (DLR) Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment (2006), `www.solarmillennium.de`.

26 Fluctuations and storage

The wind, as a direct motive power, is wholly inapplicable to a system of machine labour, for during a calm season the whole business of the country would be thrown out of gear. Before the era of steam-engines, windmills were tried for draining mines; but though they were powerful machines, they were very irregular, so that in a long tract of calm weather the mines were drowned, and all the workmen thrown idle.

William Stanley Jevons, 1865

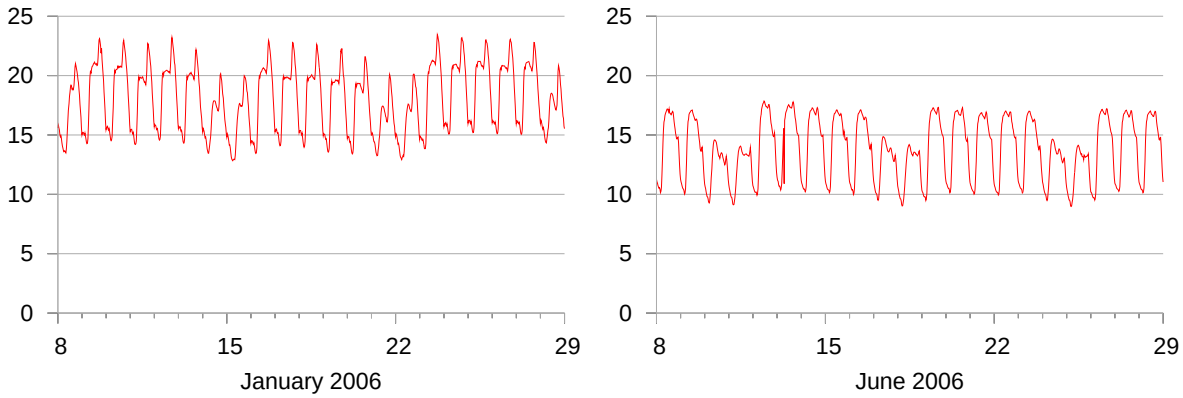


Figure 26.1. Electricity demand in Great Britain (in kWh/d per person) during two winter weeks and two summer weeks of 2006. The peaks in January are at 6pm each day. The five-day working week is evident in summer and winter. (If you'd like to obtain the national demand in GW, remember the top of the scale, 24 kWh/d per person, is the same as 60 GW per UK.)

If we kick fossil fuels and go all-out for renewables, *or* all-out for nuclear, *or* a mixture of the two, we may have a problem. Most of the big renewables are not turn-off-and-onable. When the wind blows and the sun comes out, power is there for the taking; but maybe two hours later, it's not available any more. Nuclear power stations are not usually designed to be turn-off-and-onable either. They are usually on all the time, and their delivered power can be turned down and up only on a timescale of hours. This is a problem because, on an electricity network, consumption and production must be exactly equal all the time. The electricity grid can't *store* energy. To have an energy plan that adds up every minute of every day, we therefore need *something easily turn-off-and-onable*. It's commonly assumed that the easily turn-off-and-onable something should be a *source* of power that gets turned off and on to compensate for the fluctuations of supply relative to demand (for example, a fossil fuel power station!). But another equally effective way to match supply and demand would be to have an easily turn-off-and-onable *demand* for power – a sink of power that can be turned off and on at the drop of a hat.

Either way, the easily turn-off-and-onable something needs to be a *big* something because electricity demand varies a lot (figure 26.1). The de-

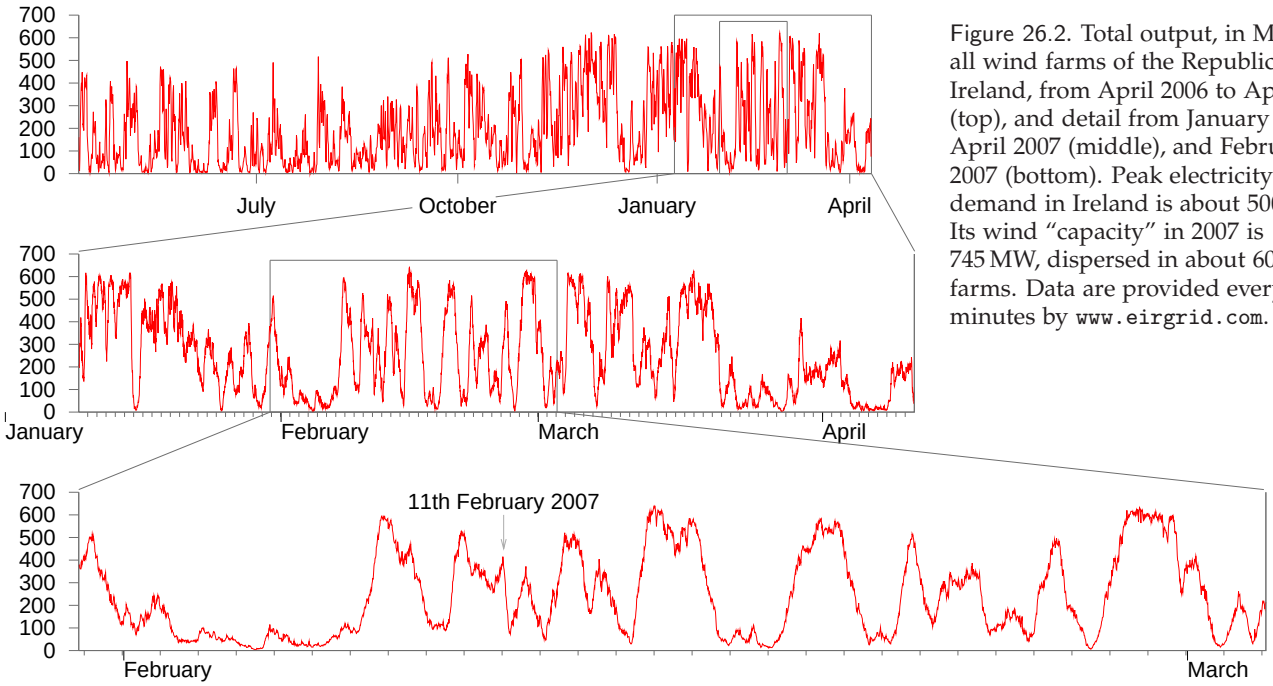


Figure 26.2. Total output, in MW, of all wind farms of the Republic of Ireland, from April 2006 to April 2007 (top), and detail from January 2007 to April 2007 (middle), and February 2007 (bottom). Peak electricity demand in Ireland is about 5000 MW. Its wind "capacity" in 2007 is 745 MW, dispersed in about 60 wind farms. Data are provided every 15 minutes by `www.eirgrid.com`.

mand sometimes changes significantly on a timescale of a few minutes. This chapter discusses how to cope with fluctuations in supply and demand, without using fossil fuels.

How much do renewables fluctuate?

However much we love renewables, we must not kid ourselves about the fact that wind does fluctuate.

Critics of wind power say: "Wind power is intermittent and unpredictable, so it can make no contribution to security of supply; if we create lots of wind power, we'll have to maintain lots of fossil-fuel power plant to replace the wind when it drops." Headlines such as "Loss of wind causes Texas power grid emergency" reinforce this view. Supporters of wind energy play down this problem: "Don't worry – *individual* wind farms may be intermittent, but taken together, the *sum* of all wind farms in different locations is much less intermittent."

Let's look at real data and try to figure out a balanced viewpoint. Figure 26.2 shows the summed output of the wind fleet of the Republic of Ireland from April 2006 to April 2007. Clearly wind *is* intermittent, even if we add up lots of turbines covering a whole country. The UK is a bit larger than Ireland, but the same problem holds there too. Between October 2006 and February 2007 there were 17 days when the output from Britain's 1632 windmills was less than 10% of their capacity. During that period there were five days when output was less than 5% and one day when it was

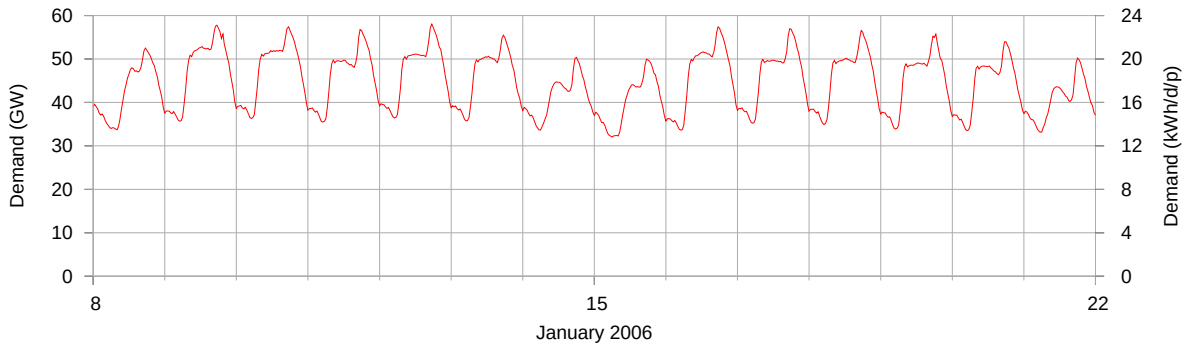


Figure 26.3. Electricity demand in Great Britain during two winter weeks of 2006. The left and right scales show the demand in national units (GW) and personal units (kWh/d per person) respectively. These are the same data as in figure 26.1.

only 2%.

Let's quantify the fluctuations in country-wide wind power. The two issues are short-term changes, and long-term lulls. Let's find the fastest short-term change in a month of Irish wind data. On 11th February 2007, the Irish wind power fell steadily from 415 MW at midnight to 79 MW at 4am. That's a slew rate of 84 MW per hour for a country-wide fleet of capacity 745 MW. (By slew rate I mean the rate at which the delivered power fell or rose – the slope of the graph on 11th February.) OK: if we scale British wind power up to a capacity of 33 GW (so that it delivers 10 GW on average), we can expect to have occasional slew rates of

$$84\,\mathrm{MW/h} \times \frac{33\,000\,\mathrm{MW}}{745\,\mathrm{MW}} = 3700\,\mathrm{MW/h},$$

assuming Britain is like Ireland. So we need to be able to either power *up* replacements for wind at a rate of 3.7 GW per hour – that's 4 nuclear power stations going from no power to full power every hour, say – *or* we need to be able to suddenly turn *down* our *demand* at a rate of 3.7 GW per hour.

Could these windy demands be met? In answering this question we'll need to talk more about "gigawatts." Gigawatts are big country-sized units of power. They are to a country what a kilowatt-hour-per-day is to a person: a nice convenient unit. The UK's average electricity consumption is about 40 GW. We can relate this national number to personal consumption: 1 kWh per day per person is equivalent to 2.5 GW nationally. So if every person uses 16 kWh per day of electricity, then national consumption is 40 GW.

Is a national slew-rate of 4 GW per hour completely outside human experience? No. Every morning, as figure 26.3 shows, British demand climbs by about 13 GW between 6.30am and 8.30am. That's a slew rate of *6.5 GW per hour*. So our power engineers already cope, every day, with slew rates bigger than 4 GW per hour on the national grid. An extra occasional slew of 4 GW per hour induced by sudden wind variations is no reasonable cause for ditching the idea of country-sized wind farms. It's a problem

just like problems that engineers have already solved. We simply need to figure out how to match ever-changing supply and demand in a grid with no fossil fuels. I'm not saying that the wind-slew problem is *already* solved – just that it is a problem of the same size as other problems that have been solved.

OK, before we start looking for solutions, we need to quantify wind's other problem: long-term lulls. At the start of February 2007, Ireland had a country-wide lull that lasted five days. This was not an unusual event, as you can see in figure 26.2. Lulls lasting two or three days happen several times a year.

There are two ways to get through lulls. Either we can store up energy somewhere before the lull, or we need to have a way of reducing demand during the entire lull. (Or a mix of the two.) If we have 33 GW of wind turbines delivering an average power of 10 GW then the amount of energy we must either store up in advance or do without during a five-day lull is

$$10\,\text{GW} \times (5 \times 24\,\text{h}) = 1200\,\text{GWh}.$$

(The gigawatt-hour (GWh) is the cuddly energy unit for nations. Britain's electricity consumption is roughly 1000 GWh per day.)

To personalize this quantity, an energy store of 1200 GWh for the nation is equivalent to an energy store of 20 kWh per person. Such an energy store would allow the nation to go without 10 GW of electricity for 5 days; or equivalently, every individual to go without 4 kWh per day of electricity for 5 days.

Coping with lulls and slews

We need to solve two problems – lulls (long periods with small renewable production), and slews (short-term changes in either supply or demand). We've quantified these problems, assuming that Britain had roughly 33 GW of wind power. To cope with lulls, we must effectively store up roughly 1200 GWh of energy (20 kWh per person). The slew rate we must cope with is 6.5 GW per hour (or 0.1 kW per hour per person).

There are two solutions, both of which could scale up to solve these problems. The first solution is a centralized solution, and the second is decentralized. The first solution stores up energy, then copes with fluctuations by turning on and off a *source* powered from the energy store. The second solution works by turning on and off a piece of *demand*.

The first solution is *pumped storage*. The second uses the batteries of the *electric vehicles* that we discussed in Chapter 20. Before I describe these solutions, let's discuss a few other ideas for coping with slew.

Other supply-side ways of coping with slew

Some of the renewables are turn-off-and-onable. If we had a lot of renewable power that was easily turn-off-and-onable, all the problems of this chapter would go away. Countries like Norway and Sweden have large and deep hydroelectric supplies which they can turn on and off. What might the options be in Britain?

First, Britain could have lots of waste incinerators and biomass incinerators – power stations playing the role that is today played by fossil power stations. If these stations were designed to be turn-off-and-onable, there would be cost implications, just as there are costs when we have extra fossil power stations that are only working part-time: their generators would sometimes be idle and sometimes work twice as hard; and most generators aren't as efficient if you keep turning them up and down, compared with running them at a steady speed. OK, leaving cost to one side, the crucial question is how big a turn-off-and-onable resource we might have. If all municipal waste were incinerated, and an equal amount of agricultural waste were incinerated, then the average power from these sources would be about 3 GW. If we built capacity equal to *twice* this power, making incinerators capable of delivering 6 GW, and thus planning to have them operate only half the time, these would be able to deliver 6 GW throughout periods of high demand, then zero in the wee hours. These power stations could be designed to switch on or off within an hour, thus coping with slew rates of 6 GW per hour – but only for a maximum slew range of 6 GW! That's a helpful contribution, but not enough slew range in itself, if we are to cope with the fluctuations of 33 GW of wind.

What about hydroelectricity? Britain's hydroelectric stations have an average load factor of 20% so they certainly have the potential to be turned on and off. Furthermore, hydro has the wonderful feature that it can be turned on and off very quickly. Glendoe, a new hydro station with a capacity of 100 MW, will be able to switch from off to on in 30 seconds, for example. That's a slew rate of 12 GW per hour in just one power station! So a sufficiently large fleet of hydro power stations should be able to cope with the slew introduced by enormous wind farms. However, the capacity of the British hydro fleet is *not* currently big enough to make much contribution to our slew problem (assuming we want to cope with the rapid loss of say 10 or 33 GW of wind power). The total capacity of traditional hydroelectric stations in Britain is only about 1.5 GW.

So simply switching on and off other renewable power sources is not going to work in Britain. We need other solutions.

Pumped storage

Pumped storage systems use cheap electricity to shove water from a downhill lake to an uphill lake; then regenerate electricity when it's valuable,

station	power (GW)	head (m)	volume (million m^3)	energy stored (GWh)
Ffestiniog	0.36	320–295	1.7	1.3
Cruachan	0.40	365–334	11.3	10
Foyers	0.30	178–172	13.6	6.3
Dinorwig	1.80	542–494	6.7	9.1

Table 26.4. Pumped storage facilities in Britain. The maximum energy storable in today's pumped storage systems is about 30 GWh.

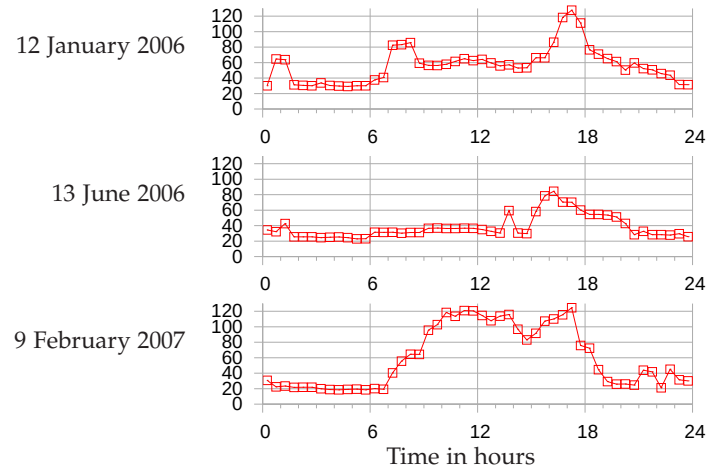


Figure 26.5. How pumped storage pays for itself. Electricity prices, in £ per MWh, on three days in 2006 and 2007.

using turbines just like the ones in hydroelectric power stations.

Britain has four pumped storage facilities, which can store 30 GWh between them (table 26.4, figure 26.6). They are typically used to store excess electricity at night, then return it during the day, especially at moments of peak demand – a profitable business, as figure 26.5 shows. The Dinorwig power station – an astonishing cathedral inside a mountain in Snowdonia – also plays an insurance role: it has enough oomph to restart the national grid in the event of a major failure. Dinorwig can switch on, from 0 to 1.3 GW power, in 12 seconds.

Dinorwig is the Queen of the four facilities. Let's review her vital statistics. The total energy that can be stored in Dinorwig is about 9 GWh. Its upper lake is about 500 m above the lower, and the working volume of 7 million m^3 flows at a maximum rate of 390 m^3/s, allowing power delivery at 1.7 GW for 5 hours. The efficiency of this storage system is 75%.

If all four pumped storage stations are switched on simultaneously, they can produce a power of 2.8 GW. They can switch on extremely fast, coping with any slew rate that demand-fluctuations or wind-fluctuations could come up with. However the capacity of 2.8 GW is not enough to replace 10 GW or 33 GW of wind power if it suddenly went missing. Nor is the total energy stored (30 GWh) anywhere near the 1200 GWh we are interested in storing in order to make it through a big lull. Could pumped

Figure 26.6. Llyn Stwlan, the upper reservoir of the Ffestiniog pumped storage scheme in north Wales. Energy stored: 1.3 GWh. Photo by Adrian Pingstone.

storage be ramped up? Can we imagine solving the entire lull problem using pumped storage alone?

Can we store 1200 GWh?

We are interested in making much bigger storage systems, storing a total of 1200 GWh (about 130 times what Dinorwig stores). And we'd like the capacity to be about 20 GW – about ten times bigger than Dinorwig's. So here is the pumped storage solution: we have to imagine creating roughly 12 new sites, each storing 100 GWh – roughly ten times the energy stored in Dinorwig. The pumping and generating hardware at each site would be the same as Dinorwig's.

Assuming the generators have an efficiency of 90%, table 26.7 shows a few ways of storing 100 GWh, for a range of height drops. (For the physics behind this table, see this chapter's endnotes.)

Ways to store 100 GWh		
drop from upper lake	working volume required (million m^3)	example size of lake area depth
500 m	40	$2\,km^2 \times 20\,m$
500 m	40	$4\,km^2 \times 10\,m$
200 m	100	$5\,km^2 \times 20\,m$
200 m	100	$10\,km^2 \times 10\,m$
100 m	200	$10\,km^2 \times 20\,m$
100 m	200	$20\,km^2 \times 10\,m$

Table 26.7. Pumped storage. Ways to store 100 GWh. For comparison with column 2, the working volume of Dinorwig is 7 million m^3, and the volume of Lake Windermere is 300 million m^3. For comparison with column 3, Rutland water has an area of 12.6 km^2; Grafham water 7.4 km^2. Carron valley reservoir is 3.9 km^2. The largest lake in Great Britain is Loch Lomond, with an area of 71 km^2.

Is it plausible that twelve such sites could be found? Certainly, we could build several more sites like Dinorwig in Snowdonia alone. Table 26.8 shows two alternative sites near to Ffestiniog where two facilities equal to Dinorwig could have been built. These sites were considered alongside Dinorwig in the 1970s, and Dinorwig was chosen.

proposed location	power (GW)	head (m)	volume (million m^3)	energy stored (GWh)
Bowydd	2.40	250	17.7	12.0
Croesor	1.35	310	8.0	6.7

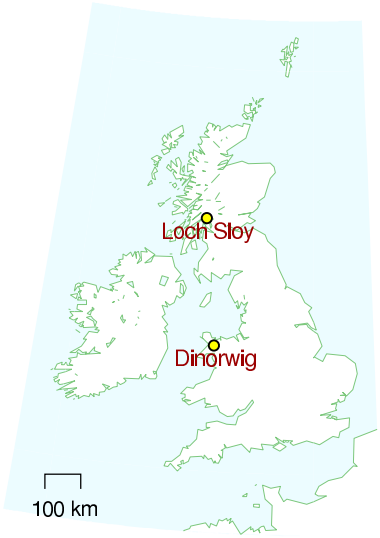
Table 26.8. Alternative sites for pumped storage facilities in Snowdonia. At both these sites the lower lake would have been a new artificial reservoir.

Pumped-storage facilities holding significantly more energy than Dinorwig could be built in Scotland by upgrading existing hydroelectric facilities. Scanning a map of Scotland, one candidate location would use Loch Sloy as its upper lake and Loch Lomond as its lower lake. There is already a small hydroelectric power station linking these lakes. Figure 26.9 shows these lakes and the Dinorwig lakes on the same scale. The height

Dinorwig is the home of a 9 GWh storage system, using Marchlyn Mawr (615E, 620N) and Llyn Peris (590E, 598N) as its upper and lower reservoirs.

Loch Sloy illustrates the sort of location where a 40 GWh storage system could be created.

Figure 26.9. Dinorwig, in the Snowdonia National Park, compared with Loch Sloy and Loch Lomond. The upper maps show 10 km by 10 km areas. In the lower maps the blue grid is made of 1 km squares. Images produced from Ordnance Survey's Get-a-map service `www.ordnancesurvey.co.uk/getamap`. Images reproduced with permission of Ordnance Survey. © Crown Copyright 2006.



difference between Loch Sloy and Loch Lomond is about 270 m. Sloy's area is about 1.5 km^2, and it can already store an energy of 20 GWh. If Loch Sloy's dam were raised by another 40 m then the extra energy that could be stored would be about 40 GWh. The water level in Loch Lomond would change by at most 0.8 m during a cycle. This is less than the normal range of annual water level variations of Loch Lomond (2 m).

Figure 26.10 shows 13 locations in Scotland with potential for pumped storage. (Most of them already have a hydroelectric facility.) If ten of these had the same potential as I just estimated for Loch Sloy, then we could store 400 GWh – one third of the total of 1200 GWh that we were aiming for.

We could scour the map of Britain for other locations. The best locations would be near to big wind farms. One idea would be to make a new artificial lake in a hanging valley (across the mouth of which a dam would

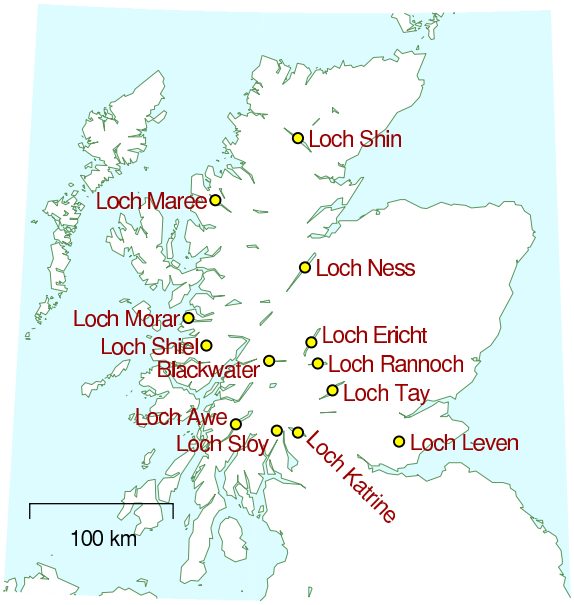


Figure 26.10. Lochs in Scotland with potential for pumped storage.

be built) terminating above the sea, with the sea being used as the lower lake.

Thinking further outside the box, one could imagine getting away from lakes and reservoirs, putting half of the facility in an underground chamber. A pumped-storage chamber one kilometre below London has been mooted.

By building more pumped storage systems, it looks as if we could increase our maximum energy store from 30 GWh to 100 GWh or perhaps 400 GWh. Achieving the full 1200 GWh that we were hoping for looks tough, however. Fortunately there is another solution.

Figure 26.11. Okinawa pumped-storage power plant, whose lower reservoir is the ocean. Energy stored: 0.2 GWh. Photo by courtesy of J-Power. `www.ieahydro.org`.

Demand management using electric vehicles

To recap our requirements: we'd like to be able to store or do without about 1200 GWh, which is 20 kWh per person; and to cope with swings in supply of up to 33 GW – that's 0.5 kW per person. These numbers are delightfully similar in size to the energy and power requirements of electric cars. The electric cars we saw in Chapter 20 had energy stores of between 9 kWh and 53 kWh. A national fleet of 30 million electric cars would store an energy similar to 20 kWh per person! Typical battery chargers draw a power of 2 or 3 kW. So simultaneously switching on 30 million battery chargers would create a change in demand of about 60 GW! The average power required to power all the nation's transport, if it were all electric, is roughly 40 or 50 GW. There's therefore a close match between the adoption of electric cars proposed in Chapter 20 and the creation of roughly 33 GW

of wind capacity, delivering 10 GW of power on average.

Here's one way this match could be exploited: electric cars could be plugged in to smart chargers, at home or at work. These smart chargers would be aware both of the value of electricity, and of the car user's requirements (for example, "my car must be fully charged by 7am on Monday morning"). The charger would sensibly satisfy the user's requirements by guzzling electricity whenever the wind blows, and switching off when the wind drops, or when other forms of demand increase. These smart chargers would provide a useful service in balancing to the grid, a service which could be rewarded financially.

We could have an especially robust solution if the cars' batteries were exchangeable. Imagine popping in to a filling station and slotting in a set of fresh batteries in exchange for your exhausted batteries. The filling station would be responsible for recharging the batteries; they could do this at the perfect times, turning up and down their chargers so that total supply and demand were always kept in balance. Using exchangeable batteries is an especially robust solution because there could be millions of spare batteries in the filling stations' storerooms. These spare batteries would provide an extra buffer to help us get through wind lulls. Some people say, "Horrors! How could I trust the filling station to look after my batteries for me? What if they gave me a duff one?" Well, you could equally well ask today "What if the filling station gave me petrol laced with water?" Myself, I'd much rather use a vehicle maintained by a professional than by a muppet like me!

Let's recap our options. We can balance fluctuating demand and fluctuating supply by switching on and off power *generators* (waste incinerators and hydroelectric stations, for example); by *storing* energy somewhere and regenerating it when it's needed; or by switching *demand* off and on.

The most promising of these options, in terms of scale, is switching on and off the power demand of electric-vehicle charging. 30 million cars, with 40 kWh of associated batteries each (some of which might be exchangeable batteries sitting in filling stations) adds up to 1200 GWh. If freight delivery were electrified too then the total storage capacity would be bigger still.

There is thus a beautiful match between wind power and electric vehicles. If we ramp up electric vehicles at the same time as ramping up wind power, roughly 3000 new vehicles for every 3 MW wind turbine, and if we ensure that the charging systems for the vehicles are smart, this synergy would go a long way to solving the problem of wind fluctuations. If my prediction about hydrogen vehicles is wrong, and hydrogen vehicles turn out to be the low-energy vehicles of the future, then the wind-with-electric-vehicles match-up that I've just described could of course be replaced by a wind-with-hydrogen match-up. The wind turbines would make electricity; and whenever electricity was plentiful, hydrogen would be produced and stored in tanks, for subsequent use in vehicles or in other applications,

such as glass production.

Other demand-management and storage ideas

There are a few other demand-management and energy-storage options, which we'll survey now.

The idea of modifying the rate of production of stuff to match the power of a renewable source is not new. Many aluminium production plants are located close to hydroelectric power stations; the more it rains, the more aluminium is produced. Wherever power is used to create stuff that is storable, there's potential for switching that power-demand on and off in a smart way. For example, reverse-osmosis systems (which make pure water from sea-water – see p92) are major power consumers in many countries (though not Britain). Another storable product is heat. If, as suggested in Chapter 21, we electrify buildings' heating and cooling systems, especially water-heating and air-heating, then there's potential for lots of easily-turn-off-and-onable power demand to be attached to the grid. Well-insulated buildings hold their heat for many hours, so there's flexibility in the timing of their heating. Moreover, we could include large thermal reservoirs in buildings, and use heat-pumps to pump heat into or out of those reservoirs at times of electricity abundance; then use a second set of heat pumps to deliver heat or cold from the reservoirs to the places where heating or cooling are wanted.

Controlling electricity demand automatically would be easy. The simplest way to do this is to have devices such as fridges and freezers listen to the frequency of the mains. When there is a shortage of power on the grid, the frequency drops below its standard value of 50 Hz; when there is a power excess, the frequency rises above 50 Hz. (It's just like a dynamo on a bicycle: when you switch the lights on, you have to pedal harder to supply the extra power; if you don't then the bike goes a bit slower.) Fridges can be modified to nudge their internal thermostats up and down just a little in response to the mains frequency, in such a way that, without ever jeopardizing the temperature of your butter, they tend to take power at times that help the grid.

Can demand-management provide a significant chunk of virtual storage? How big a sink of power are the nation's fridges? On average, a typical fridge-freezer draws about 18 W; let's guess that the number of fridges is about 30 million. So the ability to switch off all the nation's fridges for a few minutes would be equivalent to 0.54 GW of automatic adjustable power. This is quite a lot of electrical power – more than 1% of the national total – and it is similar in size to the sudden increases in demand produced when the people, united in an act of religious observance (such as watching EastEnders), simultaneously switch on their kettles. Such "TV pick-ups" typically produce increases of demand of 0.6–0.8 GW. Automatically switching off every fridge would *nearly* cover these daily blips

of concerted kettle boiling. These smart fridges could also help iron out short-time-scale fluctuations in wind power. The TV pick-ups associated with the holiest acts of observance (for example, watching England play footie against Sweden) can produce sudden increases in demand of over 2 GW. On such occasions, electricity demand and supply are kept in balance by unleashing the full might of Dinorwig.

To provide flexibility to the electricity-grid's managers, who perpetually turn power stations up and down to match supply to demand, many industrial users of electricity are on special contracts that allow the managers to switch off those users' demand at very short notice. In South Africa (where there are frequent electricity shortages), radio-controlled demand-management systems are being installed in hundreds of thousands of homes, to control air-conditioning systems and electric water heaters.

Denmark's solution

Here's how Denmark copes with the intermittency of its wind power. The Danes effectively pay to use other countries' hydroelectric facilities as storage facilities. Almost all of Denmark's wind power is exported to its European neighbours, some of whom have hydroelectric power, which they can turn down to balance things out. The saved hydroelectric power is then sold back to the Danes (at a higher price) during the next period of low wind and high demand. Overall, Danish wind is contributing useful energy, and the system as a whole has considerable security thanks to the capacity of the hydro system.

Could Britain adopt the Danish solution? We would need direct large-capacity connections to countries with lots of turn-off-and-on-able hydroelectric capacity; or a big connection to a Europe-wide electricity grid.

Norway has 27.5 GW of hydroelectric capacity. Sweden has roughly 16 GW. And Iceland has 1.8 GW. A 1.2 GW high-voltage DC interconnector to Norway was mooted in 2003, but not built. A connection to the Netherlands – the BritNed interconnector, with a capacity of 1 GW – will be built in 2010. Denmark's wind capacity is 3.1 GW, and it has a 1 GW connection to Norway, 0.6 GW to Sweden, and 1.2 GW to Germany, a total export capacity of 2.8 GW, very similar to its wind capacity. To be able to export all its excess wind power in the style of Denmark, Britain (assuming 33 GW of wind capacity) would need something like a 10 GW connection to Norway, 8 GW to Sweden, and 1 GW to Iceland.

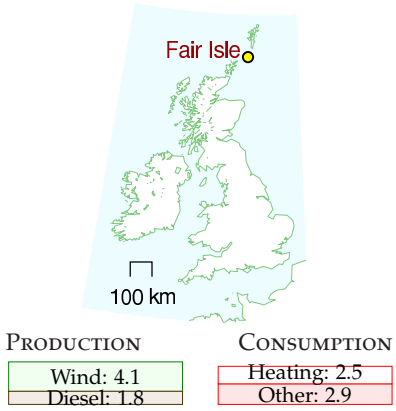


Figure 26.12. Electrical production and consumption on Fair Isle, 1995–96. All numbers are in kWh/d per person. Production exceeds consumption because 0.6 kWh/d per person were dumped.

A solution with two grids

A radical approach is to put wind power and other intermittent sources onto a separate *second* electricity grid, used to power systems that don't require reliable power, such as heating and electric vehicle battery-charging.

For over 25 years (since 1982), the Scottish island of Fair Isle (population 70, area 5.6 km^2) has had *two* electricity networks that distribute power from two wind turbines and, if necessary, a diesel-powered electricity generator. Standard electricity service is provided on one network, and electric heating is delivered by a second set of cables. The electric heating is mainly served by excess electricity from the wind-turbines that would otherwise have had to be dumped. Remote frequency-sensitive programmable relays control individual water heaters and storage heaters in the individual buildings of the community. The mains frequency is used to inform heaters when they may switch on. In fact there are up to six frequency channels per household, so the system emulates seven grids. Fair Isle also successfully trialled a kinetic-energy storage system (a flywheel) to store energy during fluctuations of wind strength on a time-scale of 20 seconds.

Electrical vehicles as generators

If 30 million electric vehicles were willing, in times of national electricity shortage, to run their chargers in reverse and put power back into the grid, then, at 2 kW per vehicle, we'd have a potential power source of 60 GW – similar to the capacity of all the power stations in the country. Even if only one third of the vehicles were connected and available at one time, they'd still amount to a potential source of 20 GW of power. If each of those vehicles made an emergency donation of 2 kWh of energy – corresponding to perhaps 20% of its battery's energy-storage capacity – then the total energy provided by the fleet would be 20 GWh – twice as much as the energy in the Dinorwig pumped storage facility.

Other storage technologies

There are lots of ways to store energy, and lots of criteria by which storage solutions are judged. Figure 26.13 shows three of the most important criteria: energy density (how much energy is stored per kilogram of storage system); efficiency (how much energy you get back per unit energy put in); and lifetime (how many cycles of energy storage can be delivered before the system needs refurbishing). Other important criteria are: the maximum rate at which energy can be pumped into or out of the storage system, often expressed as a power per kg; the duration for which energy stays stored in the system; and of course the cost and safety of the system.

Flywheels

Figure 26.15 shows a monster flywheel used to supply brief bursts of power of up to 0.4 GW to power an experimental facility. It weighs 800 t. Spinning at 225 revolutions per minute, it can store 1000 kWh, and its energy density is about 1 Wh per kg.

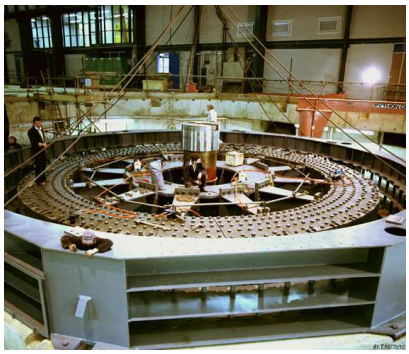
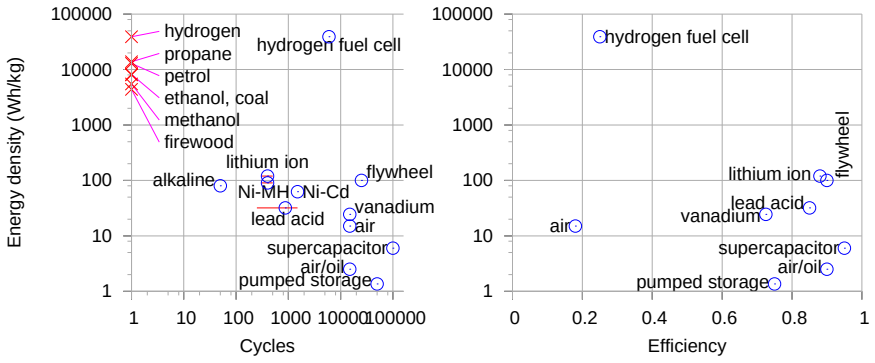


Figure 26.15. One of the two flywheels at the fusion research facility in Culham, under construction. Photo: EFDA-JET. `www.jet.efda.org`.



(a) (b)

Figure 26.13. Some properties of storage systems and fuels. (a) Energy density (on a logarithmic scale) versus lifetime (number of cycles). (b) Energy density versus efficiency. The energy densities don't include the masses of the energy systems' containers, except in the case of "air" (compressed air storage). Taking into account the weight of a cryogenic tank for holding hydrogen, the energy density of hydrogen is reduced 39 000 Wh/kg to roughly 2400 Wh/kg.

fuel	calorific value	
	(kWh/kg)	(MJ/l)
propane	13.8	25.4
petrol	13.0	34.7
diesel oil (DERV)	12.7	37.9
kerosene	12.8	37
heating oil	12.8	37.3
ethanol	8.2	23.4
methanol	5.5	18.0
bioethanol		21.6
coal	8.0	
firewood	4.4	
hydrogen	39.0	
natural gas	14.85	0.04

(a)

battery type	energy density (Wh/kg)	lifetime (cycles)
nickel-cadmium	45–80	1500
NiMH	60–120	300–500
lead-acid	30–50	200–300
lithium-ion	110–160	300–500
lithium-ion-polymer	100–130	300–500
reusable alkaline	80	50

(b)

Table 26.14. (a) Calorific values (energy densities, per kg and per litre) of some fuels (in kWh per kg and MJ per litre).
(b) Energy density of some batteries (in Wh per kg). 1 kWh = 1000 Wh.

A flywheel system designed for energy storage in a racing car can store 400 kJ (0.1 kWh) of energy and weighs 24 kg (p126). That's an energy density of 4.6 Wh per kg.

High-speed flywheels made of composite materials have energy densities up to 100 Wh/kg.

Supercapacitors

Supercapacitors are used to store small amounts of electrical energy (up to 1 kWh) where many cycles of operation are required, and charging must be completed quickly. For example, supercapacitors are favoured over batteries for regenerative braking in vehicles that do many stops and starts. You can buy supercapacitors with an energy density of 6 Wh/kg.

A US company, EEStor, claims to be able to make much better supercapacitors, using barium titanate, with an energy density of 280 Wh/kg.

Vanadium flow batteries

VRB power systems have provided a 12 MWh energy storage system for the Sorne Hill wind farm in Ireland, whose current capacity is "32 MW," increasing to "39 MW." (VRB stands for vanadium redox battery.) This storage system is a big "flow battery," a redox regenerative fuel cell, with a couple of tanks full of vanadium in different chemical states. This storage system can smooth the output of its wind farm on a time-scale of minutes, but the longest time for which it could deliver one third of the capacity (during a lull in the wind) is one hour.

A 1.5 MWh vanadium system costing $480 000 occupies 70 m^2 with a mass of 107 tons. The vanadium redox battery has a life of more than 10 000 cycles. It can be charged at the same rate that it is discharged (in contrast to lead-acid batteries which must be charged 5 times as slowly). Its efficiency is 70–75%, round-trip. The volume required is about 1 m^3 of 2-molar vanadium in sulphuric acid to store 20 kWh. (That's 20 Wh/kg.)

So to store 10 GWh would require 500 000 m^3 (170 swimming pools) – for example, tanks 2 m high covering a floor area of 500 m × 500 m.

Scaling up the vanadium technology to match a big pumped-storage system – 10 GWh – might have a noticeable effect on the world vanadium market, but there is no long-term shortage of vanadium. Current world-wide production of vanadium is 40 000 tons per year. A 10 GWh system would contain 36 000 tons of vanadium – about one year's worth of current production. Vanadium is currently produced as a by-product of other processes, and the total world vanadium resource is estimated to be 63 million tons.

"Economical" solutions

In the present world which doesn't put any cost on carbon pollution, the financial bar that a storage system must beat is an ugly alternative: storage can be emulated by simply putting up an extra gas-fired power station to meet extra demand, and shedding any excess electrical power by throwing it away in heaters.

Seasonal fluctuations

The fluctuations of supply and demand that have the longest timescale are seasonal. The most important fluctuation is that of building-heating, which goes up every winter. Current UK natural gas demand varies throughout the year, from a typical average of 36 kWh/d per person in July and August to an average of 72 kWh/d per person in December to February, with extremes of 30–80 kWh/d/p (figure 26.16).

Some renewables also have yearly fluctuations – solar power is stronger in summer and wind power is weaker.

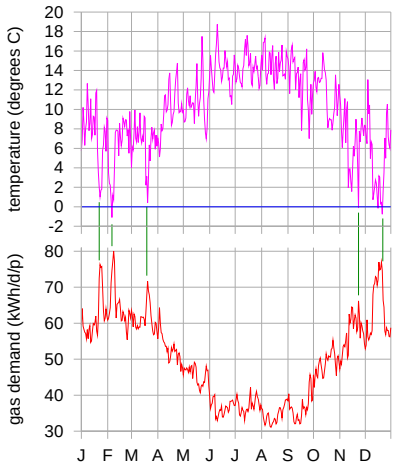


Figure 26.16. Gas demand (lower graph) and temperature (upper graph) in Britain during 2007.

How to ride through these very-long-timescale fluctuations? Electric vehicles and pumped storage are not going to help store the sort of quantities required. A useful technology will surely be long-term thermal storage. A big rock or a big vat of water can store a winter's worth of heat for a building – Chapter E discusses this idea in more detail. In the Netherlands, summer heat from roads is stored in aquifers until the winter; and delivered to buildings via heat pumps [2wmuw7].

Notes

page no.

187 *The total output of the wind fleet of the Republic of Ireland.* Data from eirgrid.com [2hxf6c].

– *"Loss of wind causes Texas power grid emergency".* [2l99ht] Actually, my reading of this news article is that this event, albeit unusual, was an example of *normal* power grid operation. The grid has industrial customers whose supply is interruptible, in the event of a mismatch between supply and demand. Wind output dropped by 1.4 GW at the same time that Texans' demand increased by 4.4 GW, causing exactly such a mismatch between supply and demand. The interruptible supplies were interrupted. Everything worked as intended.
Here is another example, where better power-system planning would have helped: "Spain wind power hits record, cut ordered." [3x2kvv] Spain's average electricity consumption is 31 GW. On Tuesday 4th March 2008, its wind generators were delivering 10 GW. "Spain's power market has become particularly sensitive to fluctuations in wind."

– *Supporters of wind energy play down this problem: "Don't worry – individual wind farms may be intermittent, but taken together, the sum of all wind farms is much less intermittent."* For an example, see the website yes2wind.com, which, on its page "debunking the myth that wind power isn't reliable" asserts that "the variation in output from wind farms distributed around the country is scarcely noticeable." www.yes2wind.com/intermittency_debunk.html

– *. . . wind* **is** *intermittent, even if we add up lots of turbines covering a whole country. The UK is a bit larger than Ireland, but the same problem holds there too.* Source: Oswald et al. (2008).

191 *Dinorwig's pumped-storage efficiency is 75%.* Figure 26.17 shows data.
Further information about Dinorwig and the alternate sites for pumped storage: Baines et al. (1983, 1986).

192 *Table 26.7.* The working volume required, V, is computed from the height drop h as follows. If ϵ is the efficiency of potential energy to electricity conversion,

$$V = 100\,\mathrm{GWh}/(\rho g h \epsilon),$$

where ρ is the density of water and g is the acceleration of gravity. I assumed the generators have an efficiency of $\epsilon = 0.9$.

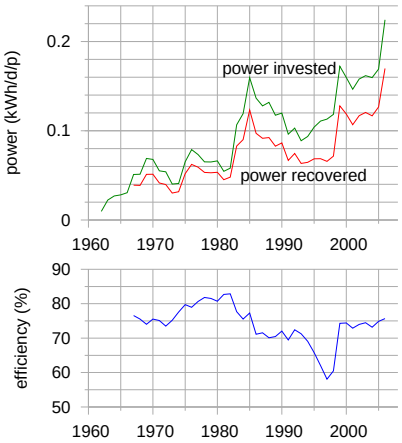


Figure 26.17. Efficiency of the four pumped storage systems of Britain.

192 *Table 26.8, Alternative sites for pumped storage facilities.* The proposed upper reservoir for Bowydd was Llyn Newydd, grid reference SH 722 470; for Croesor: Llyn Cwm-y-Foel, SH 653 466.

193 *If ten Scottish pumped storage facilities had the same potential as Loch Sloy, then we could store 400 GWh.* This rough estimate is backed up by a study by Strathclyde University [5o2xgu] which lists 14 sites having an estimated storage capacity of 514 GWh.

196 *Fridges can be modified to nudge their internal thermostats up and down . . . in response to the mains frequency.* [2n3pmb] Further links: Dynamic Demand `www.dynamicdemand.co.uk`; `www.rltec.com`; `www.responsiveload.com`.

197 *In South Africa . . . demand-management systems are being installed.* Source: [2k8h4o]

– *Almost all of Denmark's wind power is exported to its European neighbours.* Source: Sharman (2005).

198 *For over 25 years (since 1982), Fair Isle has had two electricity networks.* `www.fairisle.org.uk/FIECo/`
Wind speeds are between 3 m/s and 16 m/s most of the time; 7 m/s is the most probable speed.

199 *Figure 26.13. Storage efficiencies.* Lithium-ion batteries: 88% efficient. Source: `www.national.com/appinfo/power/files/swcap_eet.pdf`
Lead-acid batteries: 85–95%.
Source: `www.windsun.com/Batteries/Battery_FAQ.htm`
Compressed air storage: 18% efficient. Source: Lemofouet-Gatsi and Rufer (2005); Lemofouet-Gatsi (2006). See also Denholm et al. (2005).

Figure 26.18. A possible site for another 7 GWh pumped storage facility. Croesor valley is in the centre-left, between the sharp peak (Cnicht) on the left and the broader peaks (the Moelwyns) on the right.

Air/oil: hydraulic accumulators, as used for regenerative braking in trucks, are compressed-air storage devices that can be 90%-efficient round-trip and allow 70% of kinetic energy to be captured. Sources: Lemofouet-Gatsi (2006), [5cp27j].

– *Table 26.14.* Sources: Xtronics `xtronics.com/reference/energy_density.htm`; Battery University [2sxlyj]; flywheel information from Ruddell (2003).
The latest batteries with highest energy density are lithium-sulphur and lithium-sulphide batteries, which have an energy density of 300 Wh/kg.
Some disillusioned hydrogen-enthusiasts seem to be making their way up the periodic table and becoming boron-enthusiasts. Boron (assuming you will burn it to B_2O_3) has an energy density of 15 000 Wh per kg, which is nice and high. But I imagine that my main concern about hydrogen will apply to boron too: that the production of the fuel (here, boron from boron oxide) will be inefficient in energy terms, and so will the combustion process.

200 *Vanadium flow batteries.* Sources: `www.vrbpower.com`; *Ireland wind farm* [ktd7a]; *charging rate* [627ced]; *worldwide production* [5fasl7].

201 *. . . summer heat from roads is stored in aquifers. . .* [2wmuw7].

27 *Five energy plans for Britain*

If we are to get off our current fossil fuel addiction we need a plan for radical action. And the plan needs to add up. The plan also needs a political and financial roadmap. Politics and economics are not part of this book's brief, so here I will simply discuss what the technical side of a plan that adds up might look like.

There are many plans that add up. In this chapter I will describe five. Please don't take any of the plans I present as "the author's recommended solution." My sole recommendation is this:

Make sure your policies include a plan that adds up!

Each plan has a consumption side and a production side: we have to specify how much power our country will be consuming, and how that power is to be produced. To avoid the plans' taking many pages, I deal with a cartoon of our country, in which we consume power in just three forms: transport, heating, and electricity. This is a drastic simplification, omitting industry, farming, food, imports, and so forth. But I hope it's a helpful simplification, allowing us to compare and contrast alternative plans in one minute. Eventually we'll need more detailed plans, but today, we are so far from our destination that I think a simple cartoon is the best way to capture the issues.

I'll present a few plans that I believe are technically feasible for the UK by 2050. All will share the same consumption side. I emphasize again, this doesn't mean that I think this is the correct plan for consumption, or the only plan. I just want to avoid overwhelming you with a proliferation of plans. On the production side, I will describe a range of plans using different mixes of renewables, "clean coal," and nuclear power.

The current situation

The current situation in our cartoon country is as follows. Transport (of both humans and stuff) uses 40 kWh/d per person. Most of that energy is currently consumed as petrol, diesel, or kerosene. Heating of air and water uses 40 kWh/d per person. Much of that energy is currently provided by natural gas. Delivered electricity amounts to 18 kWh/d/p and uses fuel (mainly coal, gas, and nuclear) with an energy content of 45 kWh/d/p. The remaining 27 kWh/d/p goes up cooling towers (25 kWh/d/p) and is lost in the wires of the distribution network (2 kWh/d/p). The total energy input to this present-day cartoon country is 125 kWh/d per person.

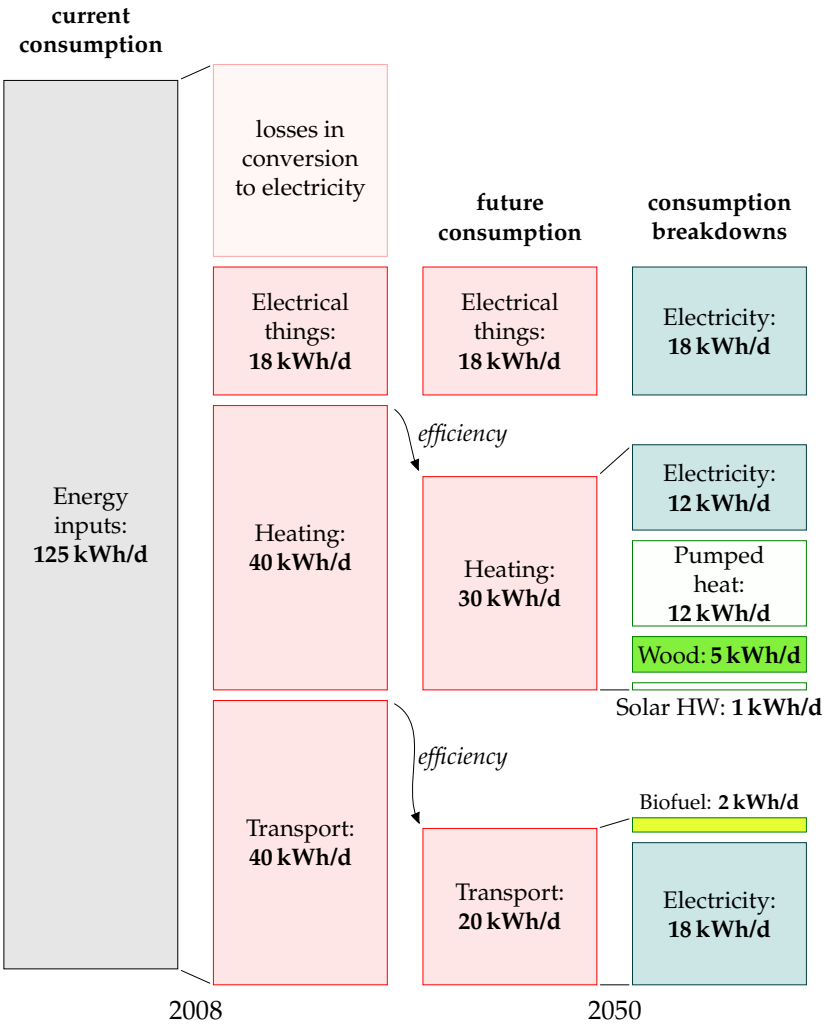


Figure 27.1. Current consumption per person in "cartoon Britain 2008" (left two columns), and a future consumption plan, along with a possible breakdown of fuels (right two columns). This plan requires that electricity supply be increased from 18 to 48 kWh/d per person of electricity.

Common features of all five plans

In my future cartoon country, the energy consumption is reduced by using more efficient technology for transport and heating.

In the five plans for the future, **transport** is largely electrified. Electric engines are more efficient than petrol engines, so the energy required for transport is reduced. Public transport (also largely electrified) is better integrated, better personalized, and better patronized. I've assumed that electrification makes transport about four times more efficient, and that economic growth cancels out some of these savings, so that the net effect is a halving of energy consumption for transport. There are a few essential vehicles that can't be easily electrified, and for those we make our own liquid fuels (for example biodiesel or biomethanol or cellulosic

bioethanol). The energy for transport is 18 kWh/d/p of electricity and 2 kWh/d/p of liquid fuels. The electric vehicles' batteries serve as an energy storage facility, helping to cope with fluctuations of electricity supply and demand. The area required for the biofuel production is about 12% of the UK (500 m^2 per person), assuming that biofuel production comes from 1%-efficient plants and that conversion of plant to fuel is 33% efficient. Alternatively, the biofuels could be imported if we could persuade other countries to devote the required (Wales-sized) area of agricultural land to biofuels for us.

In all five plans, the energy consumption of **heating** is reduced by improving the insulation of all buildings, and improving the control of temperature (through thermostats, education, and the promotion of sweater-wearing by sexy personalities). New buildings (all those built from 2010 onwards) are really well insulated and require almost no space heating. Old buildings (which will still dominate in 2050) are mainly heated by air-source heat pumps and ground-source heat pumps. Some water heating is delivered by solar panels (2.5 square metres on every house), some by heat pumps, and some by electricity. Some buildings located near to managed forests and energy-crop plantations are heated by biomass. The power required for heating is thus reduced from 40 kWh/d/p to 12 kWh/d/p of electricity, 2 kWh/d/p of solar hot water, and 5 kWh/d/p of wood.

The wood for making heat (or possibly combined heat and power) comes from nearby forests and energy crops (perhaps miscanthus grass, willow, or poplar) covering a land area of 30 000 km^2, or 500 m^2 per person; this corresponds to 18% of the UK's agricultural land, which has an area of 2800 m^2 per person. The energy crops are grown mainly on the lower-grade land, leaving the higher-grade land for food-farming. Each 500 m^2 of energy crops yields 0.5 oven dry tons per year, which has an energy content of about 7 kWh/d; of this power, about 30% is lost in the process of heat production and delivery. The final heat delivered is 5 kWh/d per person.

In these plans, I assume the current demand for **electricity** for gadgets, light, and so forth is maintained. So we still require 18 kWh(e)/d/p of electricity. Yes, lighting efficiency is improved by a switch to light-emitting diodes for most lighting, and many other gadgets will get more efficient; but thanks to the blessings of economic growth, we'll have increased the number of gadgets in our lives – for example video-conferencing systems to help us travel less.

The total consumption of electricity under this plan goes *up* (because of the 18 kWh/d/p for electric transport and the 12 kWh/d/p for heat pumps) to 48 kWh/d/p (or 120 GW nationally). This is nearly a tripling of UK electricity consumption. Where's that energy to come from?

Let's describe some alternatives. Not all of these alternatives are "sustainable" as defined in this book; but they are all low-carbon plans.

Producing lots of electricity – the components

To make lots of electricity, each plan uses some amount of onshore and offshore wind; some solar photovoltaics; possibly some solar power bought from countries with deserts; waste incineration (including refuse and agricultural waste); hydroelectricity (the same amount as we get today); perhaps wave power; tidal barrages, tidal lagoons, and tidal stream power; perhaps nuclear power; and perhaps some "clean fossil fuel," that is, coal burnt in power stations that do carbon capture and storage. Each plan aims for a total electricity production of 50 kWh/d/p on average – I got this figure by rounding up the 48 kWh/d/p of average demand, allowing for some loss in the distribution network.

Some of the plans that follow will import power from other countries. For comparison, it may be helpful to know how much of our current power is imported today. The answer is that, in 2006, the UK imported 28 kWh/d/p of fuel – 23% of its primary consumption. These imports are dominated by coal (18 kWh/d/p), crude oil (5 kWh/d/p), and natural gas (6 kWh/d/p). Nuclear fuel (uranium) is not usually counted as an import since it's easily stored.

In all five plans I will assume that we scale up municipal waste incineration so that almost all waste that can't usefully be recycled is incinerated rather than landfilled. Incinerating 1 kg per day per person of waste yields roughly 0.5 kWh/d per person of electricity. I'll assume that a similar amount of agricultural waste is also incinerated, yielding 0.6 kWh/d/p. Incinerating this waste requires roughly 3 GW of waste-to-energy capacity, a ten-fold increase over the incinerating power stations of 2008 (figure 27.2). London (7 million people) would have twelve 30-MW waste-to-energy plants like the SELCHP plant in South London (see p287). Birmingham (1 million people) would have two of them. Every town of 200 000 people would have a 10 MW waste-to-energy plant. Any fears that waste incineration at this scale would be difficult, dirty, or dangerous should be allayed by figure 27.3, which shows that many countries in Europe incinerate *far* more waste per person than the UK; these incineration-loving countries include Germany, Sweden, Denmark, the Netherlands, and Switzerland – not usually nations associated with hygiene problems! One good side-effect of this waste incineration plan is that it eliminates future methane emissions from landfill sites.

In all five plans, hydroelectricity contributes 0.2 kWh/d/p, the same as today.

Electric vehicles are used as a dynamically-adjustable load on the electricity network. The average power required to charge the electric vehicles is 45 GW (18 kWh/d/p). So fluctuations in renewables such as solar and wind can be balanced by turning up and down this load, as long as the fluctuations are not too big or lengthy. Daily swings in electricity demand are going to be bigger than they are today because of the replacement of

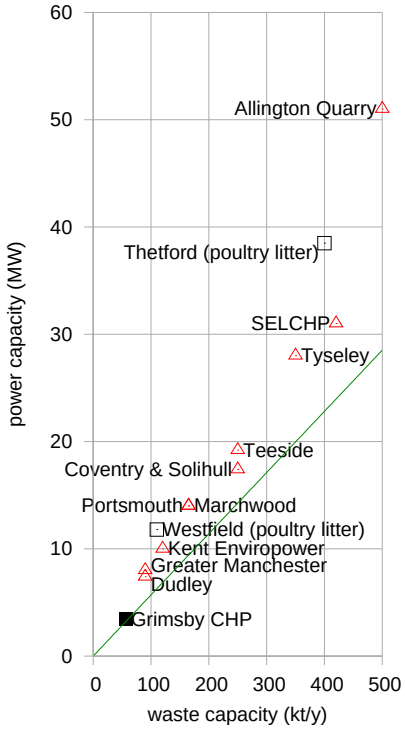


Figure 27.2. Waste-to-energy facilities in Britain. The line shows the average power production assuming 1 kg of waste → 0.5 kWh of electricity.

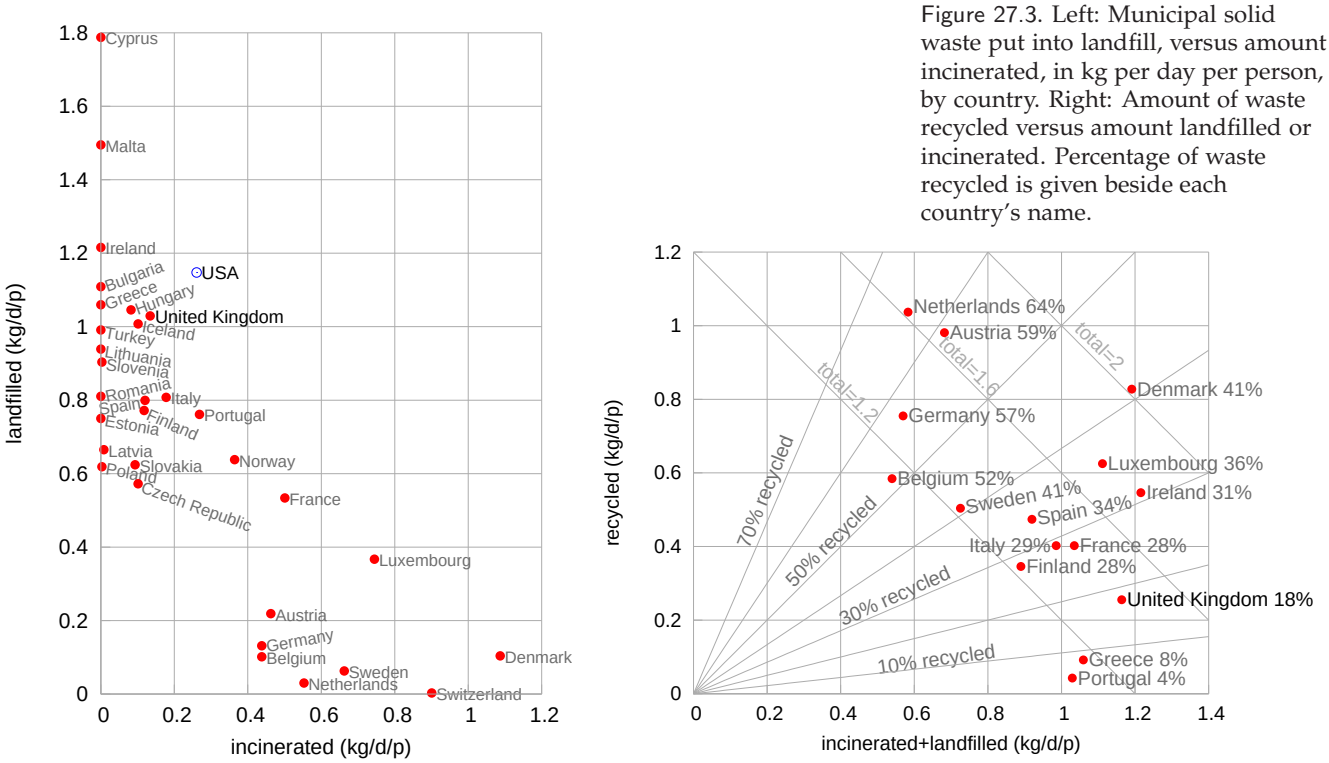


Figure 27.3. Left: Municipal solid waste put into landfill, versus amount incinerated, in kg per day per person, by country. Right: Amount of waste recycled versus amount landfilled or incinerated. Percentage of waste recycled is given beside each country's name.

gas for cooking and heating by electricity (see figure 26.16, p200). To ensure that surges in demand of 10 GW lasting up to 5 hours can be covered, all the plans would build five new pumped storage facilities like Dinorwig (or upgrade hydroelectric facilities to provide pumped storage). 50 GWh of storage is equal to five Dinorwigs, each with a capacity of 2 GW. Some of the plans that follow will require extra pumped storage beyond this. For additional insurance, all the plans would build an electricity interconnector to Norway, with a capacity of 2 GW.

Producing lots of electricity – plan D

Plan D ("D" stands for "domestic diversity") uses a lot of every possible domestic source of electricity, and depends relatively little on energy supply from other countries.

Here's where plan D gets its 50 kWh/d/p of electricity from. Wind: 8 kWh/d/p (20 GW average; 66 GW peak) (plus about 400 GWh of associated pumped storage facilities). Solar PV: 3 kWh/d/p. Waste incineration: 1.3 kWh/d/p. Hydroelectricity: 0.2 kWh/d/p. Wave: 2 kWh/d/p. Tide: 3.7 kWh/d/p. Nuclear: 16 kWh/d/p (40 GW). "Clean coal": 16 kWh/d/p (40 GW).

To get 8 kWh/d/p of wind requires a 30-fold increase in wind power over the installed power in 2008. Britain would have nearly 3 times as much wind hardware as Germany has now. Installing this much wind-power offshore over a period of 10 years would require roughly 50 jack-up barges.

Getting 3 kWh/d/p from solar photovoltaics requires 6 m^2 of 20%-efficient panels per person. Most south-facing roofs would have to be completely covered with panels; alternatively, it might be more economical, and cause less distress to the League for the Preservation of Old Buildings, to plant many of these panels in the countryside in the traditional Bavarian manner (figure 6.7, p41).

The waste incineration corresponds to 1 kg per day per person of domestic waste (yielding 0.5 kWh/d/p) and a similar amount of agricultural waste yielding 0.6 kWh/d/p; the hydroelectricity is 0.2 kWh/d/p, the same amount as we get from hydro today.

The wave power requires 16 000 Pelamis deep-sea wave devices occupying 830 km of Atlantic coastline (see the map on p73).

The tide power comes from 5 GW of tidal stream installations, a 2 GW Severn barrage, and 2.5 GW of tidal lagoons, which can serve as pumped storage systems too.

To get 16 kWh/d/p of nuclear power requires 40 GW of nukes, which is a roughly four-fold increase of the 2007 nuclear fleet. If we produced 16 kWh/d/p of nuclear power, we'd lie between Belgium, Finland, France and Sweden, in terms of per-capita production: Belgium and Finland each produce roughly 12 kWh/d/p; France and Sweden produce 19 kWh/d/p and 20 kWh/d/p respectively.

To get 16 kWh/d/p of "clean coal" (40 GW), we would have to take the current fleet of coal stations, which deliver about 30 GW, retrofit carbon-capture systems to them, which would reduce their output to 22 GW, then build another 18 GW of new clean-coal stations. This level of coal power requires an energy input of about 53 kWh/d/p of coal, which is a little bigger than the total rate at which we currently burn *all* fossil fuels at power stations, and well above the level we estimated as being "sustainable" in Chapter 23. This rate of consumption of coal is roughly three times the current rate of coal imports (18 kWh/d/p). If we didn't reopen UK coal mines, this plan would have 32% of UK electricity depending on imported coal. Reopened UK coal mines could deliver an energy input of about 8 kWh/d/p, so either way, the UK would not be self-sufficient for coal.

Do any features of this plan strike you as unreasonable or objectionable? If so, perhaps one of the next four plans is more to your liking.

Figure 27.4. Plan D

Producing lots of electricity – plan N

Plan N is the "NIMBY" plan, for people who don't like industrializing the British countryside with renewable energy facilities, and who don't want

new nuclear power stations either. Let's reveal the plan in stages.

First, we turn down all the renewable knobs from their very high settings in plan D to: wind: 2 kWh/d/p (5 GW average); solar PV: 0; wave: 0; tide: 1 kWh/d/p.

We've just lost ourselves 14 kWh/d/p (35 GW nationally) by turning down the renewables. (Don't misunderstand! Wind is still eight-fold increased over its 2008 levels.)

In the NIMBY plan, we reduce the contribution of nuclear power to 10 kWh/d/p (25 GW) – a reduction by 15 GW compared to plan D, but still a substantial increase over today's levels. 25 GW of nuclear power could, I think, be squeezed onto the existing nuclear sites, so as to avoid imposing on any new back yards. I left the clean-coal contribution unchanged at 16 kWh/d/p (40 GW). The electricity contributions of hydroelectricity and waste incineration remain the same as in plan D.

Where are we going to get an extra 50 GW from? The NIMBY says, "not in my back yard, but in someone else's." Thus the NIMBY plan pays other countries for imports of solar power from their deserts to the tune of 20 kWh/d/p (50 GW).

This plan requires the creation of five blobs each the size of London (44 km in diameter) in the transmediterranean desert, filled with solar power stations. It also requires power transmission systems to get 50 GW of power up to the UK. Today's high voltage electricity connection from France can deliver only 2 GW of power. So this plan requires a 25-fold increase in the capacity of the electricity connection from the continent. (Or an equivalent power-transport solution – perhaps ships filled with methanol or boron plying their way from desert shores.)

Having less wind power, plan N doesn't need to build in Britain the extra pumped-storage facilities mentioned in plan D, but given its dependence on sunshine, it still requires storage systems to be built somewhere to store energy from the fluctuating sun. Molten salt storage systems at the solar power stations are one option. Tapping into pumped storage systems in the Alps might also be possible. Converting the electricity to a storable fuel such as methanol is another option, though conversions entail losses and thus require more solar power stations.

This plan gets $32\% + 40\% = 72\%$ of the UK's electricity from other countries.

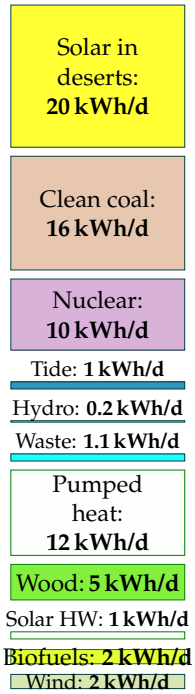


Figure 27.5. Plan N

Producing lots of electricity – plan L

Some people say "we don't want nuclear power!" How can we satisfy them? Perhaps it should be the job of this anti-nuclear bunch to persuade the NIMBY bunch that they do want renewable energy in our back yard after all.

We can create a nuclear-free plan by taking plan D, keeping all those renewables in our back yard, and doing a straight swap of nuclear for

Figure 27.6. Plan L

desert power. As in plan N, the delivery of desert power requires a large increase in transmission systems between North Africa and Britain; the Europe–UK interconnectors would need to be increased from 2 GW to at least 40 GW.

Here's where plan L gets its 50 kWh/d/p of electricity from. Wind: 8 kWh/d/p (20 GW average) (plus about 400 GWh of associated pumped storage facilities). Solar PV: 3 kWh/d/p. Hydroelectricity and waste incineration: 1.3 kWh/d/p. Wave: 2 kWh/d/p. Tide: 3.7 kWh/d/p. "Clean coal": 16 kWh/d/p (40 GW). Solar power in deserts: 16 kWh/d/p (40 GW average power).

This plan imports 64% of UK electricity from other countries.

I call this "plan L" because it aligns fairly well with the policies of the Liberal Democrats – at least it did when I first wrote this chapter in mid-2007; recently, they've been talking about "real energy independence for the UK," and have announced a zero-carbon policy, under which Britain would be a net energy *exporter*; their policy does not detail how these targets would be met.

Producing lots of electricity – plan G

Some people say "we don't want nuclear power, *and* we don't want coal!" It sounds a desirable goal, but we need a plan to deliver it. I call this "plan G," because I guess the Green Party don't want nuclear or coal, though I think not all Greens would like the rest of the plan. Greenpeace, I know, *love* wind, so plan G is dedicated to them too, because it has *lots* of wind.

I make plan G by starting again from plan D, nudging up the wave contribution by 1 kWh/d/p (by pumping money into wave research and increasing the efficiency of the Pelamis converter) and bumping up wind power fourfold (relative to plan D) to 32 kWh/d/p, so that wind delivers 64% of all the electricity. This is a 120-fold increase of British wind power over today's levels. Under this plan, *world* wind power in 2008 is multiplied by 4, with all of the increase being placed on or around the British Isles.

The immense dependence of plan G on renewables, especially wind, creates difficulties for our main method of balancing supply and demand, namely adjusting the charging rate of millions of rechargeable batteries for transport. So in plan G we have to include substantial additional pumped-storage facilities, capable of balancing out the fluctuations in wind on a timescale of days. Pumped-storage facilities equal to 400 Dinorwigs can completely replace wind for a national lull lasting 2 days. Roughly 100 of Britain's major lakes and lochs would be required for the associated pumped-storage systems.

Plan G's electricity breaks down as follows. Wind: 32 kWh/d/p (80 GW average) (plus about 4000 GWh of associated pumped-storage facilities). Solar photovoltaics: 3 kWh/d/p. Hydroelectricity and waste incineration:

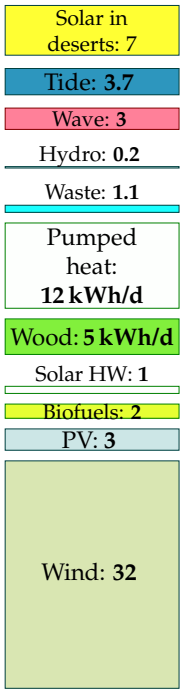


Figure 27.7. Plan G

1.3 kWh/d/p. Wave: 3 kWh/d/p. Tide: 3.7 kWh/d/p. Solar power in deserts: 7 kWh/d/p (17 GW).

This plan gets 14% of its electricity from other countries.

Producing lots of electricity – plan E

E stands for "economics." This fifth plan is a rough guess for what might happen in a liberated energy market with a strong carbon price. On a level economic playing field with a strong price signal preventing the emission of CO_2, we don't expect a diverse solution with a wide range of power-costs; rather, we expect an economically optimal solution that delivers the required power at the lowest cost. And when "clean coal" and nuclear go head to head on price, it's nuclear that wins. (Engineers at a UK electricity generator told me that the capital cost of regular *dirty* coal power stations is £1 billion per GW, about the same as nuclear; but the capital cost of "clean-coal" power, including carbon capture and storage, is roughly £2 billion per GW.) I've assumed that solar power in other people's deserts loses to nuclear power when we take into account the cost of the required 2000-km-long transmission lines (though van Voorthuysen (2008) reckons that with Nobel-prize-worthy developments in solar-powered production of chemical fuels, solar power in deserts would be the economic equal of nuclear power). Offshore wind also loses to nuclear, but I've assumed that onshore wind costs about the same as nuclear.

Here's where plan E gets its 50 kWh/d/p of electricity from. Wind: 4 kWh/d/p (10 GW average). Solar PV: 0. Hydroelectricity and waste incineration: 1.3 kWh/d/p. Wave: 0. Tide: 0.7 kWh/d/p. And nuclear: 44 kWh/d/p (110 GW).

This plan has a ten-fold increase in our nuclear power over 2007 levels. Britain would have 110 GW, which is roughly double France's nuclear fleet. I included a little tidal power because I believe a well-designed tidal lagoon facility can compete with nuclear power.

In this plan, Britain has no energy imports (except for the uranium, which, as we said before, is not conventionally counted as an import).

Figure 27.9 shows all five plans.

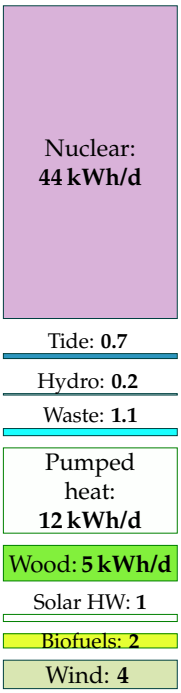


Figure 27.8. Plan E

How these plans relate to carbon-sucking and air travel

In a future world where carbon pollution is priced appropriately to prevent catastrophic climate change, we will be interested in any power scheme that can at low cost put extra carbon down a hole in the ground. Such carbon-neutralization schemes might permit us to continue flying at 2004 levels (while oil lasts). In 2004, average UK emissions of CO_2 from flying were about 0.5 t CO_2 per year per person. Accounting for the full greenhouse impact of flying, perhaps the effective emissions were about 1 t CO_2e per year per person. Now, in all five of these plans I assumed that one

1 t CO_2e means greenhouse-gas emissions equivalent to one ton of CO_2.

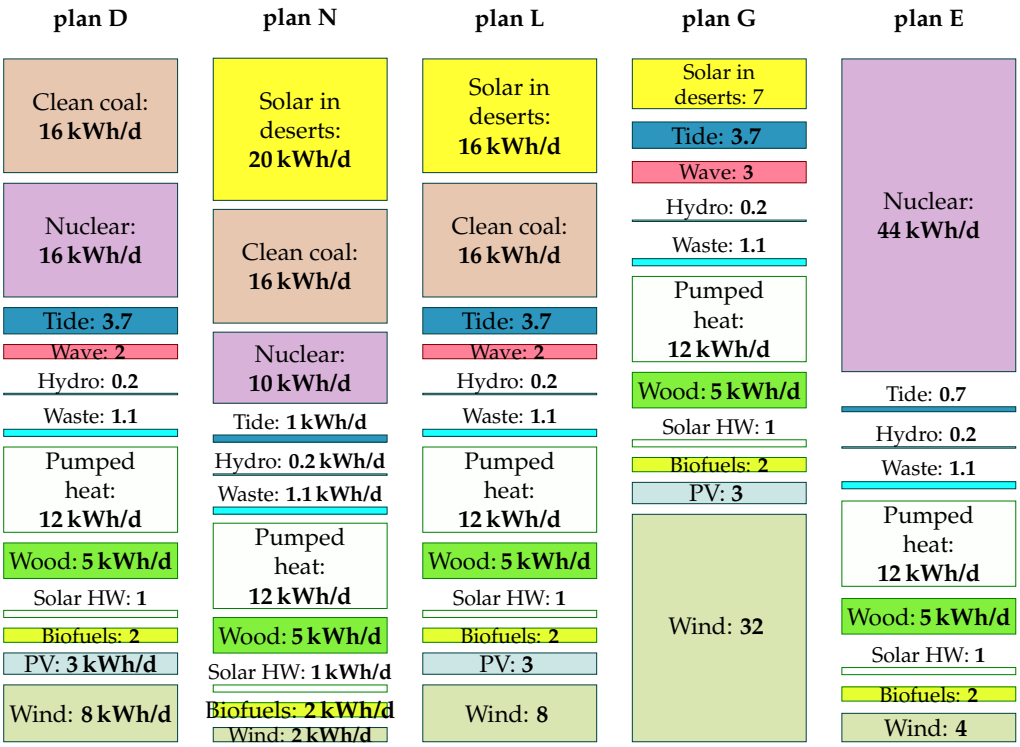


Figure 27.9. All five plans.

eighth of the UK was devoted to the production of energy crops which were then used for heating or for combined heat and power. If instead we directed all these crops to power stations with carbon capture and storage – the "clean-coal" plants that featured in three of the plans – then the amount of extra CO_2 captured would be about 1 t of CO_2 per year per person. If the municipal and agricultural waste incinerators were located at clean-coal plants too so that they could share the same chimney, perhaps the total captured could be increased to 2 t CO_2 per year per person. This arrangement would have additional costs: the biomass and waste might have to be transported further; the carbon-capture process would require a significant fraction of the energy from the crops; and the lost building-heating would have to be replaced by more air-source heat pumps. But, if carbon-neutrality is our aim, it would be worth planning ahead by seeking to locate new clean-coal plants with waste incinerators in regions close to potential biomass plantations.

"All these plans are absurd!"

If you don't like these plans, I'm not surprised. I agree that there is something unpalatable about every one of them. Feel free to make another plan that is more to your liking. But make sure it adds up!

Perhaps you will conclude that a viable plan has to involve less power consumption per capita. I might agree with that, but it's a difficult policy to sell – recall Tony Blair's response (p222) when someone suggested he should fly overseas for holidays less frequently!

Alternatively, you may conclude that we have too high a population density, and that a viable plan requires fewer people. Again, a difficult policy to sell.

Notes and further reading

page no.

206 *Incinerating 1 kg of waste yields roughly 0.5 kWh of electricity.* The calorific value of municipal solid waste is about 2.6 kWh per kg; power stations burning waste produce electricity with an efficiency of about 20%. Source: SELCHP tour guide.

207 *Figure 27.3.* Data from Eurostat, `www.epa.gov`, and `www.esrcsocietytoday.ac.uk/ESRCInfoCentre/`.

210 *The policies of the Liberal Democrats*. See `www.libdems.org.uk`: [`5os7dy`], [`yrw2oo`].

28 Putting costs in perspective

A plan on a map

Let me try to make clear the scale of the previous chapter's plans by showing you a map of Britain bearing a sixth plan. This sixth plan lies roughly in the middle of the first five, so I call it plan M (figure 28.1).

The areas and rough costs of these facilities are shown in table 28.3. For simplicity, the financial costs are estimated using today's prices for comparable facilities, many of which are early prototypes. We can expect many of the prices to drop significantly. The rough costs given here are the building costs, and don't include running costs or decommissioning costs. The "per person" costs are found by dividing the total cost by 60 million. Please remember, this is not a book about economics – that would require another 400 pages! I'm providing these cost estimates only to give a *rough* indication of the price tag we should expect to see on a plan that adds up.

I'd like to emphasize that I am not advocating this particular plan – it includes several features that I, as dictator of Britain, would not select. I've deliberately included all available technologies, so that you can try out your own plans with other mixes.

For example, if you say "photovoltaics are going to be too expensive, I'd like a plan with more wave power instead," you can see how to do it: you need to increase the wave farms eight-fold. If you don't like the wind farms' locations, feel free to move them (but where to?). Bear in mind that putting more of them offshore will increase costs. If you'd like fewer wind farms, no problem – just specify which of the other technologies you'd like instead. You can replace five of the 100 km^2 wind farms by adding one more 1 GW nuclear power station, for example.

Perhaps you think that this plan (like each of the five plans in the previous chapter) devotes unreasonably large areas to biofuels. Fine: you may therefore conclude that the demand for liquid fuels for transport must be reduced below the 2 kWh per day per person that this plan assumed; or that liquid fuels must be created in some other way.

Figure 28.1. Plan M

Cost of switching from fossil fuels to renewables

Every wind farm costs a few million pounds to build and delivers a few megawatts. As a very rough ballpark figure in 2008, installing one watt of capacity costs one pound; one kilowatt costs 1000 pounds; a megawatt of wind costs a million; a gigawatt of nuclear costs a billion or perhaps two. Other renewables are more expensive. We (the UK) currently consume a total power of roughly 300 GW, most of which is fossil fuel. So we can anticipate that a major switching from fossil fuel to renewables and/or nuclear is going to require roughly 300 GW of renewables and/or nuclear and

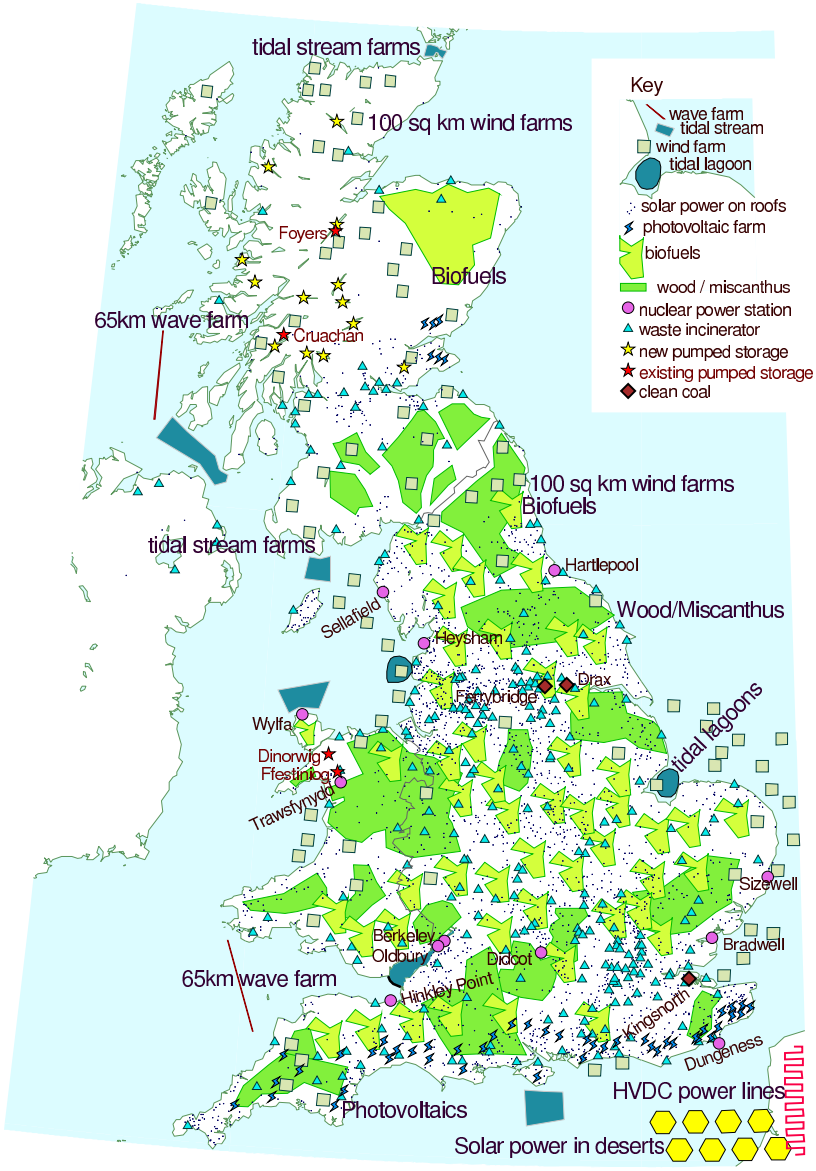


Figure 28.2. A plan that adds up, for Scotland, England, and Wales.
The grey-green squares are wind farms. Each is 100 km^2 in size and is shown to scale.
The red lines in the sea are wave farms, shown to scale.
Light-blue lightning-shaped polygons: solar photovoltaic farms – 20 km^2 each, shown to scale.
Blue sharp-cornered polygons in the sea: tide farms.
Blue blobs in the sea (Blackpool and the Wash): tidal lagoons.
Light-green land areas: woods and short-rotation coppices (to scale).
Yellow-green areas: biofuel (to scale).
Small blue triangles: waste incineration plants (not to scale).
Big brown diamonds: clean coal power stations, with cofiring of biomass, and carbon capture and storage (not to scale).
Purple dots: nuclear power stations (not to scale) – 3.3 GW average production at each of 12 sites.
Yellow hexagons across the channel: concentrating solar power facilities in remote deserts (to scale, 335 km^2 each). The pink wiggly line in France represents new HVDC lines, 2000 km long, conveying 40 GW from remote deserts to the UK.
Yellow stars in Scotland: new pumped storage facilities.
Red stars: existing pumped storage facilities.
Blue dots: solar panels for hot water on all roofs.

	Capacity	Rough cost		Average power delivered
		total	per person	
52 onshore wind farms: 5200 km^2	35 GW	£27bn – based on Lewis wind farm	£450	4.2 kWh/d/p
29 offshore wind farms: 2900 km^2	29 GW	£36bn – based on Kentish Flats, & including £3bn investment in jack-up barges.	£650	3.5 kWh/d/p
Pumped storage: 15 facilities similar to Dinorwig	30 GW	£15bn	£250	
Photovoltaic farms: 1000 km^2	48 GW	£190bn – based on Solarpark in Bavaria	£3200	2 kWh/d/p
Solar hot water panels: 1 m^2 of roof-mounted panel per person. (60 km^2 total)	2.5 GW(th) average	£72bn	£1200	1 kWh/d/p
Waste incinerators: 100 new 30 MW incinerators	3 GW	£8.5bn – based on SELCHP	£140	1.1 kWh/d/p
Heat pumps	210 GW(th)	£60bn	£1000	12 kWh/d/p
Wave farms – 2500 Pelamis, 130 km of sea	1.9 GW (0.76 GW average)	£6bn?	£100	0.3 kWh/d/p
Severn barrage: 550 km^2	8 GW (2 GW average)	£15bn	£250	0.8 kWh/d/p
Tidal lagoons: 800 km^2	1.75 GW average	£2.6bn?	£45	0.7 kWh/d/p
Tidal stream: 15 000 turbines – 2000 km^2	18 GW (5.5 GW average)	£21bn?	£350	2.2 kWh/d/p
Nuclear power: 40 stations	45 GW	£60bn – based on Olkiluoto, Finland	£1000	16 kWh/d/p
Clean coal	8 GW	£16bn	£270	3 kWh/d/p
Concentrating solar power in deserts: 2700 km^2	40 GW average	£340bn – based on Solúcar	£5700	16 kWh/d/p
Land in Europe for 1600 km of HVDC power lines: 1200 km^2	50 GW	£1bn – assuming land costs £7500 per ha	£15	
2000 km of HVDC power lines	50 GW	£1bn – based on German Aerospace Center estimates	£15	
Biofuels: 30 000 km^2		(cost not estimated)		2 kWh/d/p
Wood/Miscanthus: 31 000 km^2		(cost not estimated)		5 kWh/d/p

Table 28.3. Areas of land and sea required by plan M, and rough costs. Costs with a question mark are for technologies where no accurate cost is yet available from prototypes. "1 GW(th)" denotes one GW of thermal power.

thus have a cost in the ballpark of £300 billion. The rough costs in table 28.3 add up to £870bn, with the solar power facilities dominating the total – the photovoltaics cost £190bn and the concentrating solar stations cost £340bn. Both these costs might well come down dramatically as we learn by doing. A government report leaked by the Guardian in August 2007 estimates that achieving "20% by 2020" (that is, 20% of all energy from renewables, which would require an increase in renewable power of 80 GW) could cost "up to £22 billion" (which would average out to £1.7 billion per year). Even though this estimate is smaller than the £80 billion that the rule of thumb I just mentioned would have suggested, the authors of the leaked report seem to view £22 billion as an "unreasonable" cost, preferring a target of just 9% renewables. (Another reason they give for disliking the "20% by 2020" target is that the resulting greenhouse gas savings "risk making the EU emissions trading scheme redundant." Terrifying thought!)

Other things that cost a billion

Billions are big numbers and hard to get a feel for. To try to help put the cost of kicking fossil fuels into perspective, let's now list some other things that also come in billions of pounds, or in billions per year. I'll also express many of these expenditures "per person," dividing the total by an appropriate population.

Perhaps the most relevant quantity to compare with is the money we *already* spend on energy every year. In the UK, the money spent on energy by final users is £75 billion per year, and the total market value of all energy consumed is £130 billion per year. So the idea of spending £1.7 billion per year on investment in future energy infrastructure seems not at all unreasonable – it is less than 3% of our current expenditure on energy!

Another good comparison to make is with our annual expenditure on insurance: some of the investments we need to make offer an uncertain return – just like insurance. UK individuals and businesses spend £90bn per year on insurance.

Subsidies

£56 billion over 25 years: the cost of decommissioning the UK's nuclear power stations. That's the 2004 figure; in 2008 it was up to £73 billion (£1200 per person in the UK). [6eoyhg]

Transport

£4.3 billion: the cost of London Heathrow Airport's Terminal 5. (£72 per person in the UK.)
£1.9 billion: the cost of widening 91 km of the M1 (from junction 21 to 30, figure 28.4). [yu8em5]. (£32 per person in the UK.)

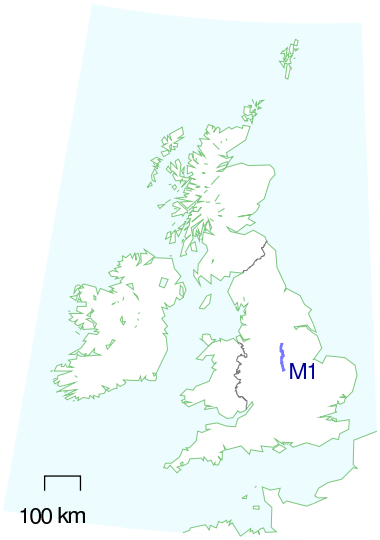


Figure 28.4. The M1, from junction 21 to 30.

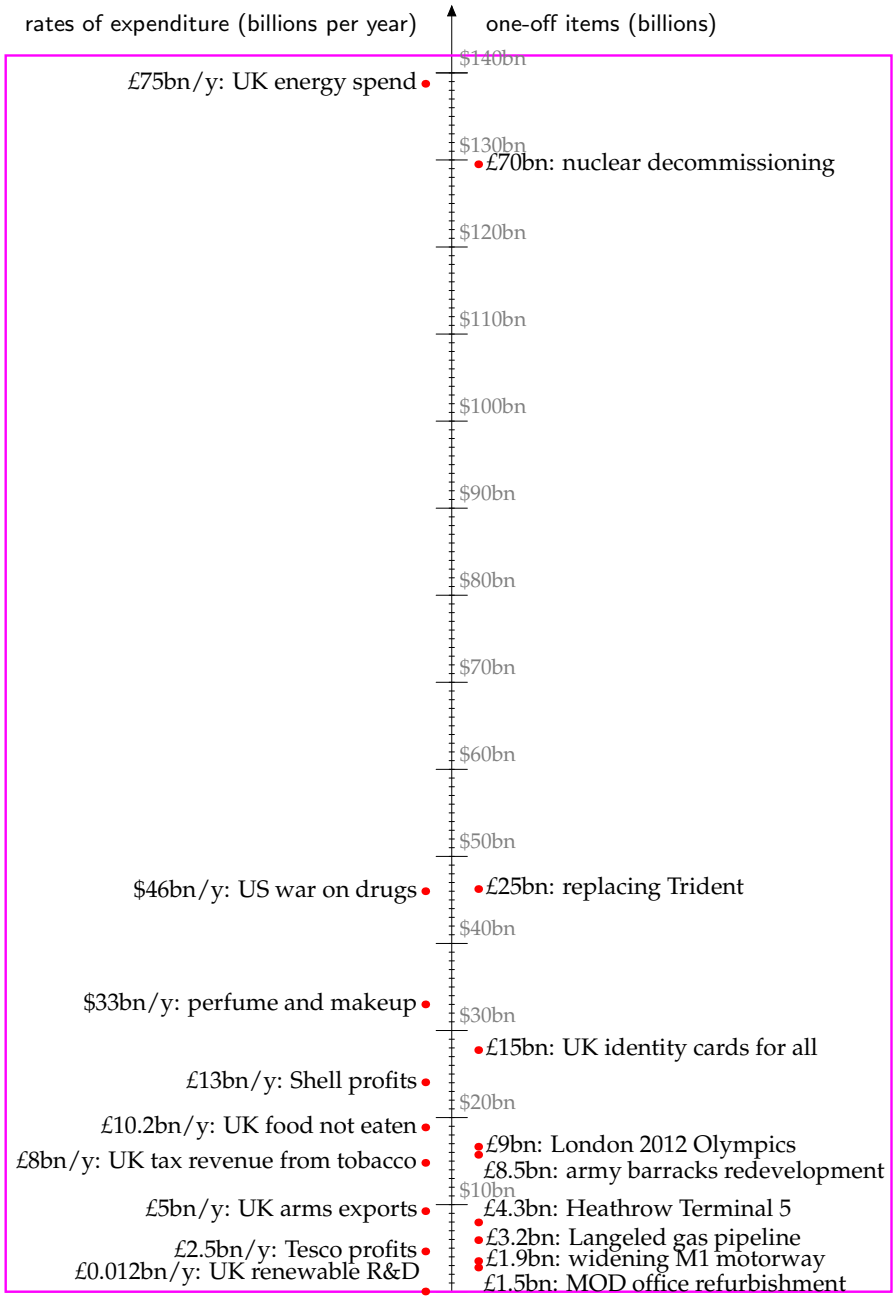


Figure 28.5. Things that run into billions. The scale down the centre has large ticks at $10 billion intervals and small ticks at $1 billion intervals.

Special occasions

Cost of the London 2012 Olympics: £2.4 billion; no, I'm sorry, £5 billion [3x2cr4]; or perhaps £9 billion [2dd4mz]. (£150 per person in the UK.)

Business as usual

£2.5 billion/y: Tesco's profits (announced 2007). (£42 per year per person in the UK.)
£10.2 billion/y: spent by British people on food that they buy but do not eat. (£170 per year per person in the UK.)
£11 billion/y: BP's profits (2006).
£13 billion/y: Royal Dutch Shell's profits (2006).
$40 billion/y. Exxon's profits (2006).
$33 billion/y. World expenditure on perfumes and make-up.
$700 billion per year: USA's expenditure on foreign oil (2008). ($2300 per year per person in the USA.)

Government business as usual

£1.5 billion: the cost of refurbishment of Ministry of Defence offices. (Private Eye No. 1176, 19th January 2007, page 5.) (£25 per person in the UK.)
£15 billion: the cost of introducing UK identity card scheme [7vlxp]. (£250 per person in the UK.)

Planning for the future

£3.2 billion: the cost of the Langeled pipeline, which ships gas from Norwegian producers to Britain. The pipeline's capacity is 20 billion m^3 per year, corresponding to a power of 25 GW. [6x4nvu] [39g2wz] [3ac8sj]. (£53 per person in the UK.)

Tobacco taxes and related games

£8 billion/y: annual revenue from tobacco taxes in the UK [y7kg26]. (£130 per year per person in the UK.) The European Union spends almost €1 billion a year subsidising tobacco farming. www.ash.org.uk
$46 billion/y: Annual cost of the USA's "War on drugs." [r9fcf] ($150 per year per person in the USA.)

Space

$1.7 billion: the cost of one space shuttle. ($6 per person in the USA.)

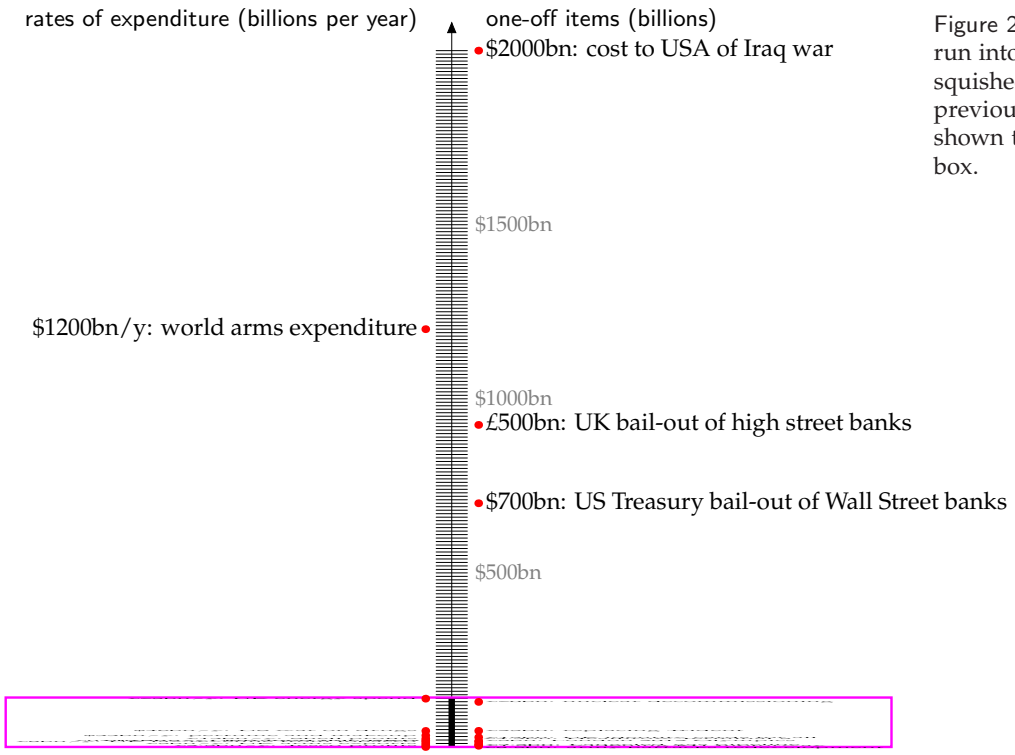


Figure 28.6. A few more things that run into billions. The vertical scale is squished 20-fold compared with the previous figure, figure 28.5, which is shown to scale inside the magenta box.

Banks

$700 billion: in October 2008, the US government committed $700 billion to bailing out Wall Street, and ...
£500 billion: the UK government committed £500 billion to bailing out British banks.

Military

£5 billion per year: UK's arms exports (£83 per year per person in the UK), of which £2.5 billion go to the Middle East, and £1 billion go to Saudi Arabia. Source: Observer, 3 December 2006.
£8.5 billion: cost of redevelopment of army barracks in Aldershot and Salisbury Plain. (£140 per person in the UK.)
£3.8 billion: the cost of two new aircraft carriers (£63 per person in the UK). `news.bbc.co.uk/1/low/scotland/6914788.stm`
$4.5 billion per year: the cost of not making nuclear weapons – the US Department of Energy's budget allocates at least $4.5 billion per year to "stockpile stewardship" activities to maintain the nuclear stockpile *without* nuclear testing and *without* large-scale production of new weapons. ($15 per year per person in America.)

£10–25 billion: the cost of replacing Trident, the British nuclear weapon system. (£170–420 per person in the UK.) [ysncks].
$63 billion: American donation of "military aid" (i.e. weapons) to the Middle East over 10 years – roughly half to Israel, and half to Arab states. [2vq59t] ($210 per person in the USA.)
$1200 billion per year: world expenditure on arms [ym46a9]. ($200 per year per person in the world.)
$2000 billion or more: the cost, to the USA, of the [99bpt] Iraq war according to Nobel prize-winning economist Joseph Stiglitz. ($7000 per person in America.)

According to the Stern review, the global cost of averting dangerous climate change (if we act now) is $440 billion per year ($440 per year per person, if shared equally between the 1 billion richest people). In 2005, the US government alone spent $480 billion on wars and preparation for wars. The total military expenditure of the 15 biggest military-spending countries was $840 billion.

*Expenditure that does **not** run into billions*

£0.012 billion per year: the smallest item displayed in figure 28.5 is the UK government's annual investment in renewable-energy research and development. (£0.20 per person in the UK, per year.)

Notes and further reading

215 *Figure 28.2.* I've assumed that the solar photovoltaic farms have a power per unit area of 5 W/m^2, the same as the Bavaria farm on p41, so each farm on the map delivers 100 MW on average. Their total average production would be 5 GW, which requires roughly 50 GW of peak capacity (that's 16 times Germany's PV capacity in 2006).
The yellow hexagons representing concentrating solar power have an average power of 5 GW each; it takes two of these hexagons to power one of the "blobs" of Chapter 25.

217 *A government report leaked by the Guardian…* The Guardian report, 13th August 2007, said [2bmuod] "Government officials have secretly briefed ministers that Britain has no hope of getting remotely near the new European Union renewable energy target that Tony Blair signed up to in the spring - and have suggested that they find ways of wriggling out of it."
The leaked document is at [3g8nn8].

219 *…perfume…* Source: Worldwatch Institute
www.worldwatch.org/press/news/2004/01/07/

221 *…wars and preparation for wars…* www.conscienceonline.org.uk

– *Government investment in renewable-energy-related research and development.* In 2002–3, the UK Government's commitment to renewable-energy-related R&D was £12.2 million. Source: House of Lords Science and Technology Committee, 4th Report of Session 2003–04. [3jo7q2]
Comparably small is the government's allocation to the Low Carbon Buildings Programme, £0.018bn/y shared between wind, biomass, solar hot water/PV, ground-source heat pumps, micro-hydro and micro CHP.

29 What to do now

Unless we act now, not some time distant but now, these consequences, disastrous as they are, will be irreversible. So there is nothing more serious, more urgent or more demanding of leadership.

Tony Blair, 30 October 2006

a bit impractical actually...

Tony Blair, two months later, responding to the suggestion that he should *show* leadership by not flying to Barbados for holidays.

What we should do depends in part on our motivation. Recall that on page 5 we discussed three motivations for getting off fossil fuels: the end of cheap fossil fuels; security of supply; and climate change. Let's assume first that we have the climate-change motivation – that we want to reduce carbon emissions radically. (Anyone who doesn't believe in climate change can skip this section and rejoin the rest of us on page 223.)

What to do about carbon pollution

We are not on track to a zero-carbon future. Long-term investment is not happening. Carbon sequestration companies are not thriving, even though the advice from climate experts and economic experts alike is that sucking carbon dioxide from thin air will very probably be necessary to avoid dangerous climate change. Carbon is not even being captured at any coal power stations (except for one tiny prototype in Germany).

Why not?

The principal problem is that carbon pollution is not priced correctly. And there is no confidence that it's going to be priced correctly in the future. When I say "correctly," I mean that the price of emitting carbon dioxide should be big enough such that every running coal power station has carbon capture technology fitted to it.

Solving climate change is a complex topic, but in a single crude brush-stroke, here is the solution: the price of carbon dioxide must be such that people *stop burning coal without capture*. Most of the solution is captured in this one brush-stroke because, in the long term, coal is the big fossil fuel. (Trying to reduce emissions from oil and gas is of secondary importance because supplies of both oil and gas are expected to decline over the next 50 years.)

So what do politicians need to do? They need to ensure that all coal power stations have carbon capture fitted. The first step towards this goal is for government to finance a large-scale demonstration project to sort out the technology for carbon capture and storage; second, politicians need to

change the long-term regulations for power stations so that the perfected technology is adopted everywhere. My simple-minded suggestion for this second step is to pass a law that says that – from some date – *all coal power stations must use carbon capture*. However, most democratic politicians seem to think that the way to close a stable door is to create a market in permits-to-leave-doors-open. So, if we conform to the dogma that climate change should be solved through markets, what's the market-based way to ensure we achieve our simple goal – all coal power stations to have carbon capture? Well, we can faff around with carbon trading – trading of permits to emit carbon and of certificates of carbon-capture, with one-tonne carbon-capture certificates being convertible into one-tonne carbon-emission permits. But coal station owners will invest in carbon capture and storage only if they are convinced that the price of carbon is going to be high enough for long enough that carbon-capturing facilities will pay for themselves. Experts say that a long-term guaranteed carbon price of something like \$100 per ton of CO_2 will do the trick.

So politicians need to agree long-term reductions in CO_2 emissions that are sufficiently strong that investors have confidence that the price of carbon will rise permanently to at least \$100 per ton of CO_2. Alternatively they could issue carbon pollution permits in an auction with a fixed minimum price. Another way would be for governments to underwrite investment in carbon capture by guaranteeing that they will redeem captured-carbon certificates for \$100 per ton of CO_2, whatever happens to the market in carbon-emission permits.

I still wonder whether it would be wisest to close the stable door directly, rather than fiddling with an international market that is merely *intended* to encourage stable door-closing.

> *Britain's energy policy just doesn't stack up. It won't deliver security. It won't deliver on our commitments on climate change. It falls short of what the world's poorest countries need.*
>
> Lord Patten of Barnes, Chair of Oxford University task force on energy and climate change, 4 June 2007.

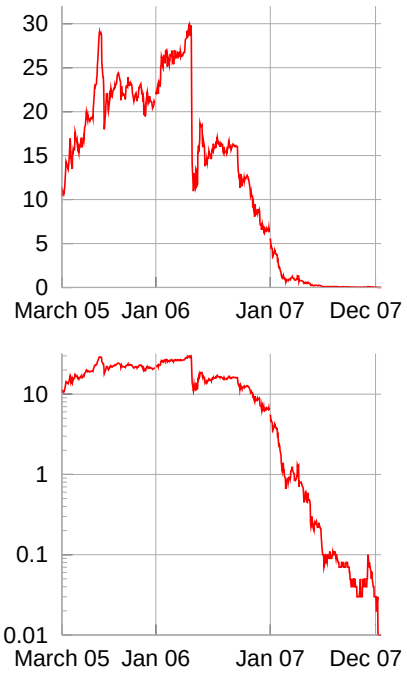


Figure 29.1. A fat lot of good that did! The price, in euro, of one ton of CO_2 under the first period of the European emissions trading scheme. Source: `www.eex.com`.

What to do about energy supply

Let's now expand our set of motivations, and assume that we want to get off fossil fuels in order to ensure security of energy supply.

What should we do to bring about the development of non-fossil energy supply, and of efficiency measures? One attitude is "Just let the market handle it. As fossil fuels become expensive, renewables and nuclear power will become relatively cheaper, and the rational consumer will prefer efficient technologies." I find it odd that people have such faith in markets, given how regularly markets give us things like booms and busts, credit crunches, and collapses of banks. Markets may be a good

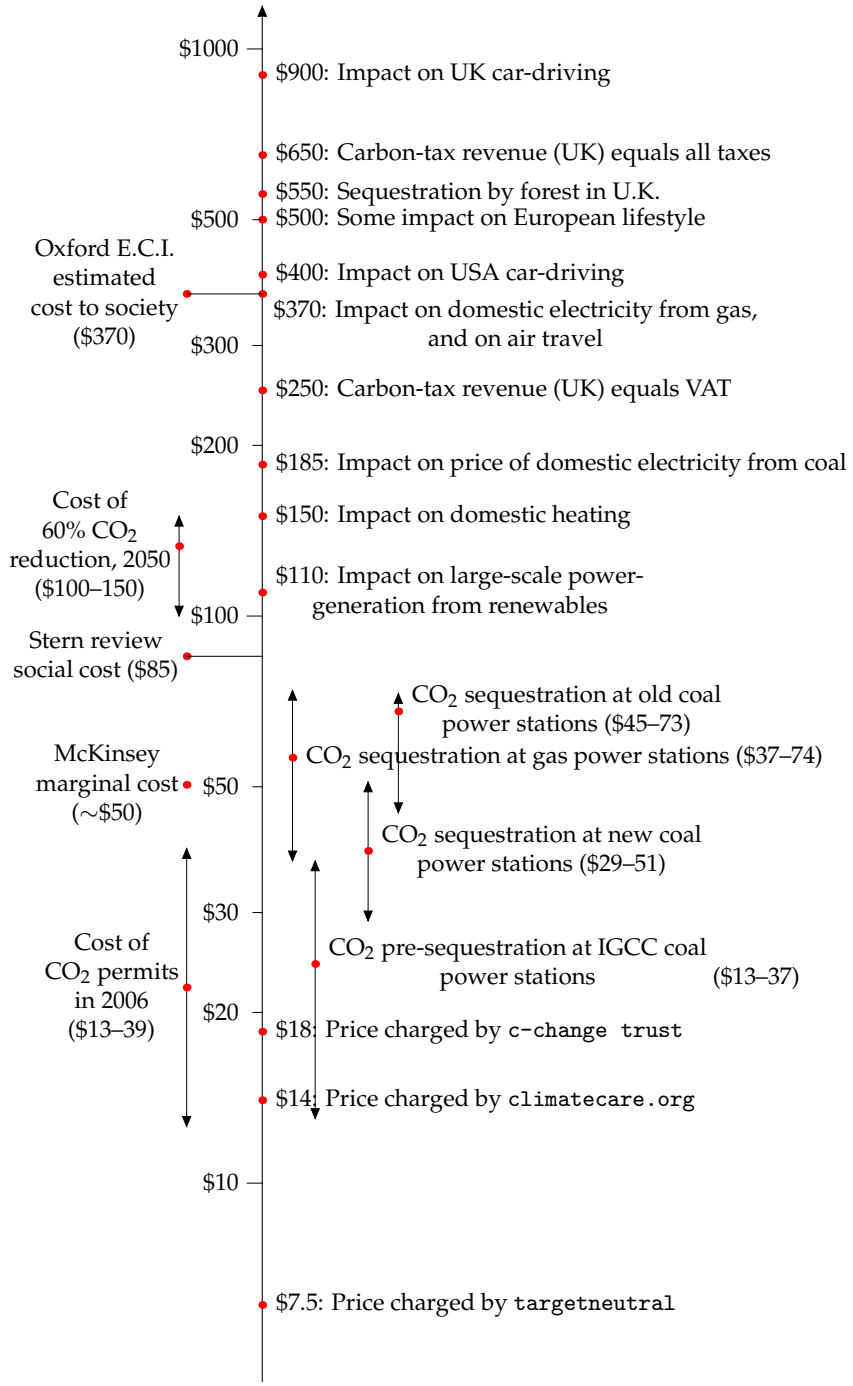


Figure 29.2. What price would CO_2 need to have in order to drive society to make significant changes in CO_2 pollution?
The diagram shows carbon dioxide costs (per tonne) at which particular investments will become economical, or particular behaviours will be significantly impacted, assuming that a major behavioural impact on activities like flying and driving results if the carbon cost doubles the cost of the activity.
As the cost rises through $20–70 per tonne, CO_2 would become sufficiently costly that it would be economical to add carbon sequestration to new and old power stations.
A price of $110 per tonne would transform large-scale renewable electricity-generation projects that currently cost 3p per kWh more than gas from pipedreams into financially viable ventures. For example, the proposed Severn barrage would produce tidal power with a cost of 6p per kWh, which is 3.3p above a typical selling price of 2.7p per kWh; if each 1000 kWh from the barrage avoided one ton of CO_2 pollution at a value of £60 per ton, the Severn barrage would more than pay for itself.
At $150 per tonne, domestic users of gas would notice the cost of carbon in their heating bills.
A price of $250 per tonne would increase the effective cost of a barrel of oil by $100.
At $370, carbon pollution would cost enough to significantly reduce people's inclination to fly.
At $500 per tonne, average Europeans who didn't change their lifestyle might spend 12% of income on the carbon costs of driving, flying, and heating their homes with gas.
And at $900 per tonne, the carbon cost of driving would be noticeable.

way of making some short-term decisions – about investments that will pay off within ten years or so – but can we expect markets to do a good job of making decisions about energy, decisions whose impacts last many decades or centuries?

If the free market is allowed to build houses, we end up with houses that are poorly insulated. Modern houses are only more energy-efficient thanks to legislation.

The free market isn't responsible for building roads, railways, dedicated bus lanes, car parks, or cycle paths. But road-building and the provision of car parks and cycle paths have a significant impact on people's transport choices. Similarly, planning laws, which determine *where* homes and workplaces may be created and *how densely* houses may be packed into land have an overwhelming influence on people's future travelling behaviour. If a new town is created that has no rail station, it is unlikely that the residents of that town will make long-distance journeys by rail. If housing and workplaces are more than a few miles apart, many people will feel that they have no choice but to drive to work.

One of the biggest energy-sinks is the manufacture of stuff; in a free market, many manufacturers supply us with stuff that has planned obsolescence, stuff that has to be thrown away and replaced, so as to make more business for the manufacturers.

So, while markets may play a role, it's silly to say "let the market handle it *all*." Surely we need to talk about legislation, regulations, and taxes.

Greening the tax system

> *We need to profoundly revise all of our taxes and charges. The aim is to tax pollution – notably fossil fuels – more, and tax work less.*
>
> Nicolas Sarkozy, President of France

At present it's much cheaper to buy a new microwave, DVD player, or vacuum cleaner than to get a malfunctioning one fixed. That's crazy.

This craziness is partly caused by our tax system, which taxes the labour of the microwave-repair man, and surrounds his business with time-consuming paperwork. He's doing a *good* thing, repairing my microwave! – yet the tax system makes it difficult for him to do business.

The idea of "greening the tax system" is to move taxes from "goods" like labour, to "bads" like environmental damage. Advocates of environmental tax reform suggest balancing tax cuts on "goods" by equivalent tax increases on "bads," so that the tax reforms are revenue-neutral.

Carbon tax

The most important tax to increase, if we want to promote fossil-fuel-free technologies, is a tax on carbon. The price of carbon needs to be high

enough to promote investment in alternatives to fossil fuels, and investment in efficiency measures. Notice this is exactly the same policy as was suggested in the previous section. So, whether our motivation is fixing climate change, or ensuring security of supply, the policy outcome is the same: we need a carbon price that is stable and high. Figure 29.2 indicates very roughly the various carbon prices that are required to bring about various behaviour changes and investments; and the much lower prices charged by organizations that claim to "offset" greenhouse-gas emissions. How best to arrange a high carbon price? Is the European emissions trading scheme (figure 29.1) the way to go? This question lies in the domain of economists and international policy experts. The view of Cambridge economists Michael Grubb and David Newbery is that the European emissions trading scheme is not up to the job – "current instruments will not deliver an adequate investment response."

The Economist recommends a carbon tax as the primary mechanism for government support of clean energy sources. The Conservative Party's Quality of Life Policy Group also recommends increasing environmental taxes and reducing other taxes – "a shift from *pay as you earn* to *pay as you burn*." The Royal Commission on Environmental Pollution also says that the UK should introduce a carbon tax. "It should apply upstream and cover all sectors."

So, there's clear support for a big carbon tax, accompanied by reductions in employment taxes, corporation taxes, and value-added taxes. But taxes and markets alone are not going to bring about all the actions needed. The tax-and-market approach fails if consumers sometimes choose irrationally, if consumers value short-term cash more highly than long-term savings, or if the person choosing what to buy doesn't pay all the costs associated with their choice.

Indeed many brands are "*reassuringly expensive*." Consumer choice is not determined solely by price signals. Many consumers care more about image and perception, and some deliberately buy expensive.

Once an inefficient thing is bought, it's too late. It's essential that inefficient things should not be manufactured in the first place; or that the consumer, when buying, should feel influenced not to buy inefficient things.

Here are some further examples of failures of the free market.

The admission barrier

Imagine that carbon taxes are sufficiently high that a new super-duper low-carbon gizmo would cost 5% less than its long-standing high-carbon rival, the Dino-gizmo, *if* it were mass-produced in the same quantities. Thanks to clever technology, the Eco-gizmo's carbon emissions are a fantastic 90% lower than the Dino-gizmo's. It's clear that it would be good for society if everyone bought Eco-gizmos now. But at the moment, sales of the new Eco-gizmo are low, so the per-unit economic costs are higher than the

Dino-gizmo's. Only a few tree-huggers and lab coats will buy the Eco-Gizmo, and Eco-Gizmo Inc. will go out of business.

Perhaps government interventions are necessary to oil the transition and give innovation a chance. Support for research and development? Tax-incentives favouring the new product (like the tax-incentives that oiled the transition from leaded to unleaded petrol)?

The problem of small cost differences

Imagine that Eco-Gizmo Inc. makes it from tadpole to frog, and that carbon taxes are sufficiently high that an Eco-gizmo indeed costs 5% less than its long-standing high-carbon rival from Dino-appliances, Inc. Surely the carbon taxes will now do their job, and all consumers will buy the low-carbon gizmo? Ha! First, many consumers don't care too much about a 5% price difference. Image is everything. Second, if they feel at all threatened by the Eco-gizmo, Dino-appliances, Inc. will relaunch their Dino-gizmo, emphasizing that it's more patriotic, announcing that it's now available in green, and showing cool people sticking with the old faithful Dino-gizmo. "Real men buy Dino-gizmos." If this doesn't work, Dino will issue press-releases saying scientists haven't ruled out the possibility that long-term use of the Eco-gizmo might cause cancer, highlighting the case of an old lady who was tripped up by an Eco-gizmo, or suggesting that Eco-gizmos harm the lesser spotted fruit bat. Fear, Uncertainty, Doubt. As a back-up plan, Dino-appliances could always buy up the Eco-gizmo company. The winning product will have nothing to do with energy saving if the economic incentive to the consumer is only 5%.

How to fix this problem? Perhaps government should simply ban the sales of the Dino-gizmo (just as it banned sales of leaded-petrol cars)?

The problem of Larry and Tina

Imagine that Larry the landlord rents out a flat to Tina the tenant. Larry is responsible for maintaining the flat and providing the appliances in it, and Tina pays the monthly heating and electricity bills. Here's the problem: Larry feels no incentive to invest in modifications to the flat that would reduce Tina's bills. He could install more-efficient lightbulbs, and plug in a more economical fridge; these eco-friendly appliances would easily pay back their extra up-front cost over their long life; but it's Tina who would benefit, not Larry. Similarly, Larry feels little incentive to improve the flat's insulation or install double-glazing, especially when he takes into account the risk that Tina's boyfriend Wayne might smash one of the windows when drunk. In principle, in a perfect market, Larry and Tina would both make the "right" decisions: Larry would install all the energy-saving features, and would charge Tina a slightly higher monthly rent; Tina would recognize that the modern and well-appointed flat would be cheaper to live

in and would thus be happy to pay the higher rent; Larry would demand an increased deposit in case of breakage of the expensive new windows; and Tina would respond rationally and banish Wayne. However, I don't think that Larry and Tina can ever deliver a perfect market. Tina is poor, so has difficulty paying large deposits. Larry strongly wishes to rent out the flat, so Tina mistrusts his assurances about the property's low energy bills, suspecting Larry of exaggeration.

So some sort of intervention is required, to get Larry and Tina to do the right thing – for example, government could legislate a huge tax on inefficient appliances; ban from sale all fridges that do not meet economy benchmarks; require all flats to meet high standards of insulation; or introduce a system of mandatory independent flat assessment, so that Tina could read about the flat's energy profile before renting.

Investment in research and development

> *We deplore the minimal amounts that the Government have committed to renewable-energy-related research and development (£12.2 million in 2002-03). . . . If resources other than wind are to be exploited in the United Kingdom this has to change. We could not avoid the conclusion that the Government are not taking energy problems sufficiently seriously.*
>
> House of Lords Science and Technology Committee

> *The absence of scientific understanding often leads to superficial decision-making. The 2003 energy white paper was a good example of that. I would not like publicly to call it amateurish but it did not tackle the problem in a realistic way.*
>
> Sir David King, former Chief Scientist

> *Serving on the government's Renewables Advisory Board . . . felt like watching several dozen episodes of* Yes Minister *in slow motion. I do not think this government has ever been serious about renewables.*
>
> Jeremy Leggett, founder of Solarcentury

I think the numbers speak for themselves. Just look at figure 28.5 (p218) and compare the billions spent on office refurbishments and military toys with the hundred-fold smaller commitment to renewable-energy-related research and development. It takes decades to develop renewable technologies such as tidal stream power, concentrating solar power, and photovoltaics. Nuclear fusion takes decades too. All these technologies need up-front support if they are going to succeed.

Individual action

People sometimes ask me "What should *I* do?" Table 29.3 indicates eight simple personal actions I'd recommend, and a *very* rough indication of the savings associated with each action. Terms and conditions apply. Your savings will depend on your starting point. The numbers in table 29.3 assume the starting point of an above-average consumer.

Simple action	possible saving
Put on a woolly jumper and turn down your heating's thermostat (to 15 or 17 °C, say). Put individual thermostats on all radiators. Make sure the heating's off when no-one's at home. Do the same at work.	20 kWh/d
Read all your meters (gas, electricity, water) every week, and identify easy changes to reduce consumption (e.g., switching things off). Compare competitively with a friend. Read the meters at your place of work too, creating a perpetual live energy audit.	4 kWh/d
Stop flying.	35 kWh/d
Drive less, drive more slowly, drive more gently, carpool, use an electric car, join a car club, cycle, walk, use trains and buses.	20 kWh/d
Keep using old gadgets (e.g. computers); don't replace them early.	4 kWh/d
Change lights to fluorescent or LED.	4 kWh/d
Don't buy clutter. Avoid packaging.	20 kWh/d
Eat vegetarian, six days out of seven.	10 kWh/d

Table 29.3. Eight simple personal actions.

Whereas the above actions are easy to implement, the ones in table 29.4 take a bit more planning, determination, and money.

Major action	possible saving
Eliminate draughts.	5 kWh/d
Double glazing.	10 kWh/d
Improve wall, roof, and floor insulation.	10 kWh/d
Solar hot water panels.	8 kWh/d
Photovoltaic panels.	5 kWh/d
Knock down old building and replace by new.	35 kWh/d
Replace fossil-fuel heating by ground-source or air-source heat pumps.	10 kWh/d

Table 29.4. Seven harder actions.

Finally, table 29.5 shows a few runners-up: some simple actions with small savings.

Action	possible saving
Wash laundry in cold water.	0.5 kWh/d
Stop using a tumble-dryer; use a clothes-line or airing cupboard.	0.5 kWh/d

Table 29.5. A few more simple actions with small savings.

Notes and further reading

page no.

222 *"a bit impractical actually"* The full transcript of the interview with Tony Blair (9 January 2007) is here [2ykfgw]. Here are some more quotes from it:
Interviewer: Have you thought of perhaps not flying to Barbados for a holiday and not using all those air miles?
Tony Blair: I would, frankly, be reluctant to give up my holidays abroad.
Interviewer: It would send out a clear message though wouldn't it, if we didn't see that great big air journey off to the sunshine? ... – a holiday closer to home?
Tony Blair: Yeah – but I personally think these things are a bit impractical actually to expect people to do that. I think that what we need to do is to look at how you make air travel more energy efficient, how you develop the new fuels that will allow us to burn less energy and emit less. How – for example – in the new frames for the aircraft, they are far more energy efficient.
I know everyone always – people probably think the Prime Minister shouldn't go on holiday at all, but I think if what we do in this area is set people unrealistic targets, you know if we say to people we're going to cancel all the cheap air travel ... You know, I'm still waiting for the first politician who's actually running for office who's going to come out and say it – and they're not.

The other quote: "Unless we act now, not some time distant but now, these consequences, disastrous as they are, will be irreversible. So there is nothing more serious, more urgent or more demanding of leadership." is Tony Blair speaking at the launch of the Stern review, 30 October 2006 [2nsvx2]. See also [yxq5xk] for further comment.

225 *Environmental tax reform.* See the Green Fiscal Commission, www.greenfiscalcommission.org.uk.

226 The Economist *recommends a carbon tax.* "Nuclear power's new age," *The Economist*, September 8th 2007.

– *The Conservative Party's Quality of Life Policy Group* – Gummer et al. (2007).

30 Energy plans for Europe, America, and the World

Figure 30.1 shows the power consumptions of lots of countries or regions, versus their gross domestic products (GDPs). It is a widely held assumption that human development and growth are good things, so when sketching world plans for sustainable energy I am going to assume that all the countries with low GDP per capita are going to progress rightwards in figure 30.1. And as their GDPs increase, it's inevitable that their power consumptions will increase too. It's not clear what consumption we should plan for, but I think that the average European level (125 kWh per day per person) seems a reasonable assumption; alternatively, we could assume that efficiency measures, like those envisaged in Cartoon Britain in Chapters 19–28, allow all countries to attain a European standard of living with a lower power consumption. In the consumption plan on p204, Cartoon Britain's consumption fell to about 68 kWh/d/p. Bearing in mind that Cartoon Britain doesn't have much industrial activity, perhaps it would be sensible to assume a slightly higher target, such as Hong Kong's 80 kWh/d/p.

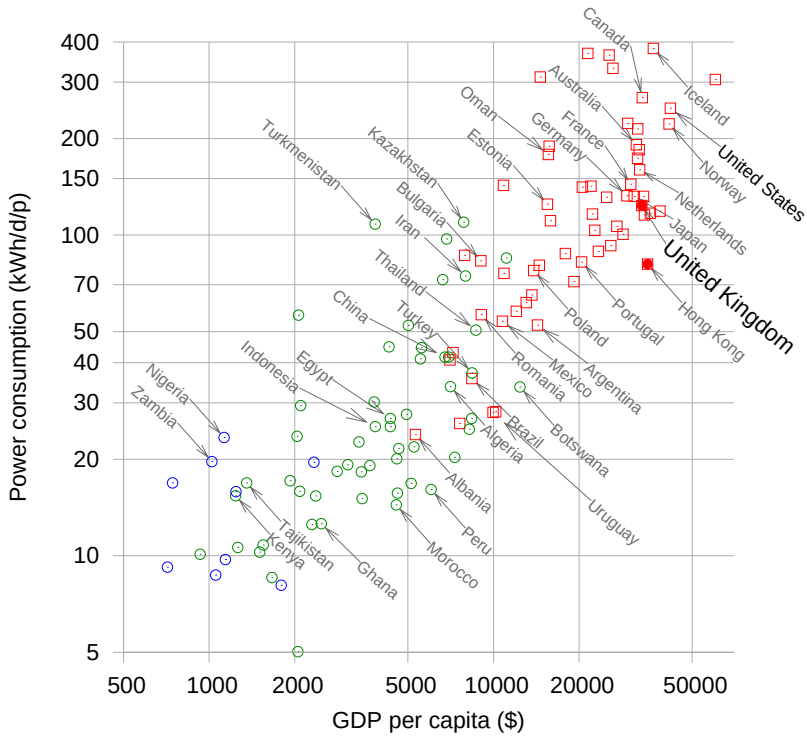


Figure 30.1. Power consumption per capita versus GDP per capita, in purchasing-power-parity US dollars. Data from UNDP Human Development Report, 2007. Squares show countries having "high human development;" circles, "medium" or "low." Both variables are on logarithmic scales. Figure 18.4 shows the same data on normal scales.

Redoing the calculations for Europe

Can Europe live on renewables?

Europe's average population density is roughly half of Britain's, so there is more land area in which to put enormous renewable facilities. The area of the European Union is roughly 9000 m^2 per person. However, many of the renewables have lower power density in Europe than in Britain: most of Europe has less wind, less wave, and less tide. Some parts do have more hydro (in Scandanavia and Central Europe); and some have more solar. Let's work out some rough numbers.

Wind

The heart of continental Europe has lower typical windspeeds than the British Isles – in much of Italy, for example, windspeeds are below 4 m/s. Let's guess that one fifth of Europe has big enough wind-speeds for economical wind-farms, having a power density of 2 W/m^2, and then assume that we give those regions the same treatment we gave Britain in Chapter 4, filling 10% of them with wind farms. The area of the European Union is roughly 9000 m^2 per person. So wind gives

$$\frac{1}{5} \times 10\% \times 9000\,m^2 \times 2\,W/m^2 = 360\,W$$

which is 9 kWh/d per person.

Hydroelectricity

Hydroelectric production in Europe totals 590 TWh/y, or 67 GW; shared between 500 million, that's 3.2 kWh/d per person. This production is dominated by Norway, France, Sweden, Italy, Austria, and Switzerland. If every country doubled its hydroelectric facilities – which I think would be difficult – then hydro would give 6.4 kWh/d per person.

Wave

Taking the whole Atlantic coastline (about 4000 km) and multiplying by an assumed average production rate of 10 kW/m, we get 2 kWh/d per person. The Baltic and Mediterranean coastlines have no wave resource worth talking of.

Tide

Doubling the estimated total resource around the British Isles (11 kWh/d per person, from Chapter 14) to allow for French, Irish and Norwegian tidal resources, then sharing between a population of 500 million, we get

2.6 kWh/d per person. The Baltic and Mediterranean coastlines have no tidal resource worth talking of.

Figure 30.2. A solar water heater providing hot water for a family in Michigan. The system's pump is powered by the small photovoltaic panel on the left.

Solar photovoltaics and thermal panels on roofs

Most places are sunnier than the UK, so solar panels would deliver more power in continental Europe. 10 m^2 of roof-mounted photovoltaic panels would deliver about 7 kWh/d in all places south of the UK. Similarly, 2 m^2 of water-heating panels could deliver on average 3.6 kWh/d of low-grade thermal heat. (I don't see much point in suggesting having more than 2 m^2 per person of water-heating panels, since this capacity would already be enough to saturate typical demand for hot water.)

What else?

The total so far is $9 + 6.4 + 2 + 2.6 + 7 + 3.6 = 30.6$ kWh/d per person. The only resources not mentioned so far are geothermal power, and large-scale solar farming (with mirrors, panels, or biomass).

Geothermal power might work, but it's still in the research stages. I suggest treating it like fusion power: a good investment, but not to be relied on.

So what about solar farming? We could imagine using 5% of Europe (450 m^2 per person) for solar photovoltaic farms like the Bavarian one in figure 6.7 (which has a power density of 5 W/m^2). This would deliver an average power of

$$5\,\mathrm{W/m^2} \times 450\,\mathrm{m^2} = 54\,\mathrm{kWh/d\ per\ person}.$$

Solar PV farming would, therefore, add up to something substantial. The main problem with photovoltaic panels is their cost. Getting power during the winter is also a concern!

Energy crops? Plants capture only 0.5 W/m^2 (figure 6.11). Given that Europe needs to feed itself, the non-food energy contribution from plants in Europe can never be enormous. Yes, there will be some oil-seed rape here and some forestry there, but I don't imagine that the total non-food contribution of plants could be more than 12 kWh/d per person.

The bottom line

Let's be realistic. Just like Britain, *Europe can't live on its own renewables*. So if the aim is to get off fossil fuels, Europe needs nuclear power, or solar power in other people's deserts (as discussed on p179), or both.

Redoing the calculations for North America

The average American uses 250 kWh/d per day. Can we hit that target with renewables? What if we imagine imposing shocking efficiency measures (such as efficient cars and high-speed electric trains) such that Americans were reduced to the misery of living on the mere 125 kWh/d of an average European or Japanese citizen?

Wind

A study by Elliott et al. (1991) assessed the wind energy potential of the USA. The windiest spots are in North Dakota, Wyoming, and Montana. They reckoned that, over the whole country, 435 000 km^2 of windy land could be exploited without raising too many hackles, and that the electricity generated would be 4600 TWh per year, which is 42 kWh per day per person if shared between 300 million people. Their calculations assumed an average power density of 1.2 W/m^2, incidentally – smaller than the 2 W/m^2 we assumed in Chapter 4. The area of these wind farms, 435 000 km^2, is roughly the same as the area of California. The amount of wind hardware required (assuming a load factor of 20%) would be a capacity of about 2600 GW, which would be a 200-fold increase in wind hardware in the USA.

Offshore wind

If we assume that shallow offshore waters with an area equal to the sum of Delaware and Connecticut (20 000 km^2, a substantial chunk of all shallow waters on the east coast of the USA) are filled with offshore wind farms having a power density of 3 W/m^2, we obtain an average power of 60 GW. That's 4.8 kWh/d per person if shared between 300 million people. The wind hardware required would be 15 times the total wind hardware currently in the USA.

Geothermal

I mentioned the MIT geothermal energy study (Massachusetts Institute of Technology, 2006) in Chapter 16. The authors are upbeat about the potential of geothermal energy in North America, especially in the western states where there is more hotter rock. "With a reasonable investment in R&D, enhanced geothermal systems could provide 100 GW(e) or more of cost-competitive generating capacity in the next 50 years. Further, enhanced geothermal systems provide a secure source of power for the long term." Let's assume they are right. 100 GW of electricity is 8 kWh/d per person when shared between 300 million.

Hydro

The hydroelectric facilities of Canada, the USA, and Mexico generate about 660 TWh per year. Shared between 500 million people, that amounts to 3.6 kWh/d per person. Could the hydroelectric output of North America be doubled? If so, hydro would provide 7.2 kWh/d per person.

What else?

The total so far is $42 + 4.8 + 8 + 7.2 = 62$ kWh/d per person. Not enough for even a European existence! I could discuss various other options such as the sustainable burning of Canadian forests in power stations. But rather than prolong the agony, let's go immediately for a technology that adds up: concentrating solar power.

Figure 30.3 shows the area within North America that would provide everyone there (500 million people) with an average power of 250 kWh/d.

The bottom line

North America's *non-solar* renewables aren't enough for North America to live on. But when we include a massive expansion of solar power, there's enough. So North America needs solar in its own deserts, or nuclear power, or both.

Redoing the calculations for the world

How can 6 billion people obtain the power for a European standard of living – 80 kWh per day per person, say?

Wind

The exceptional spots in the world with strong steady winds are the central states of the USA (Kansas, Oklahoma); Saskatchewan, Canada; the southern extremities of Argentina and Chile; northeast Australia; northeast and northwest China; northwest Sudan; southwest South Africa; Somalia; Iran; and Afghanistan. And everywhere offshore except for a tropical strip 60 degrees wide centred on the equator.

For our global estimate, let's go with the numbers from Greenpeace and the European Wind Energy Association: "the total available wind resources worldwide are estimated at 53 000 TWh per year." That's 24 kWh/d per person.

Hydro

Worldwide, hydroelectricity currently contributes about 1.4 kWh/d per person.

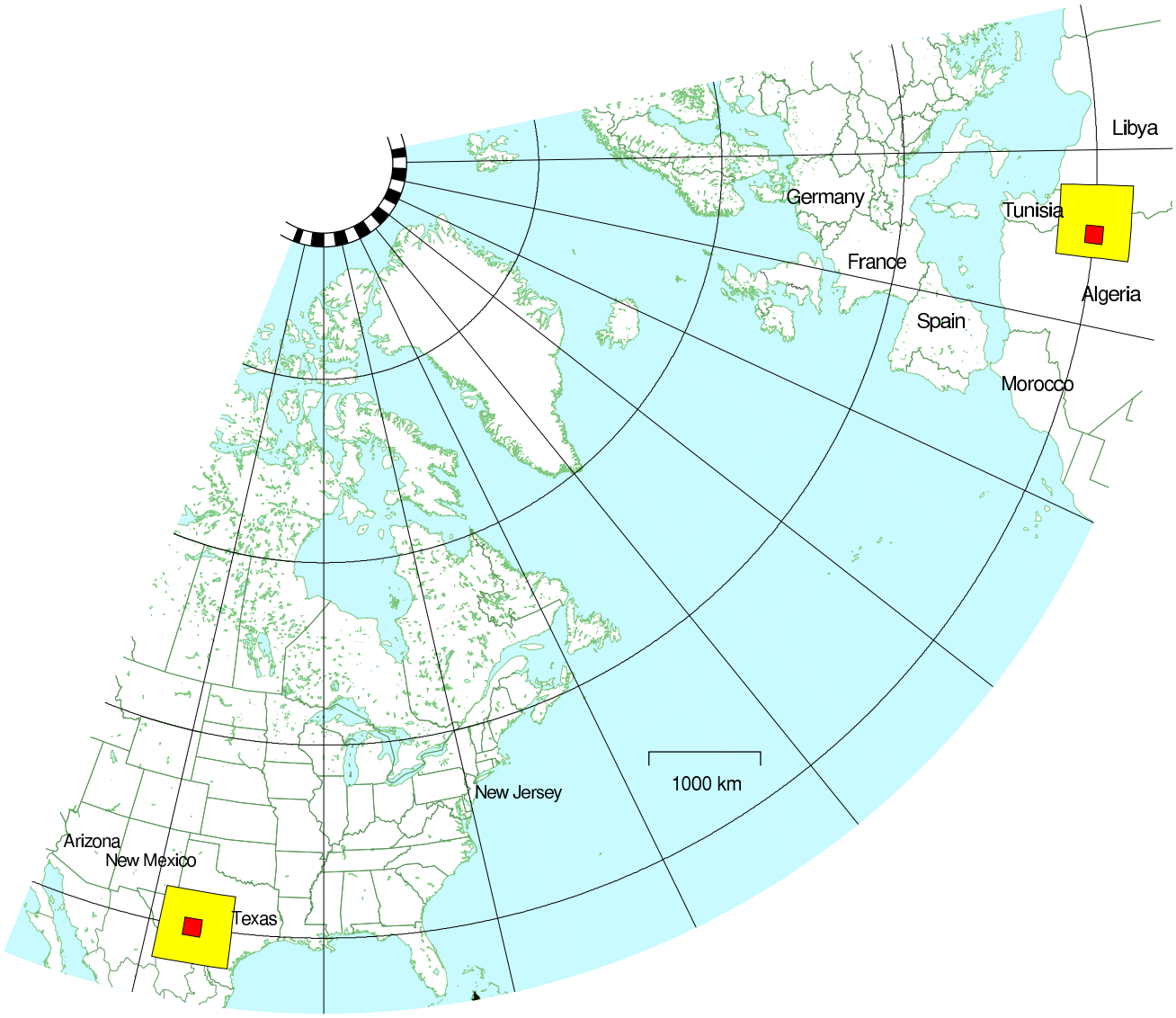


Figure 30.3. The little square strikes again. The 600 km by 600 km square in North America, completely filled with concentrating solar power, would provide enough power to give 500 million people the average American's consumption of 250 kWh/d.

This map also shows the square of size 600 km by 600 km in Africa, which we met earlier. I've assumed a power density of 15 W/m^2, as before.

The area of one yellow square is a little bigger than the area of Arizona, and 16 times the area of New Jersey. Within each big square is a smaller 145 km by 145 km square showing the area required in the desert – one New Jersey – to supply 30 million people with 250 kWh per day per person.

From the website www.ieahydro.org, "The International Hydropower Association and the International Energy Agency estimate the world's total technical feasible hydro potential at 14 000 TWh/year [6.4 kWh/d per person on the globe], of which about 8000 TWh/year [3.6 kWh/d per person] is currently considered economically feasible for development. Most of the potential for development is in Africa, Asia and Latin America."

Tide

There are several places in the world with tidal resources on the same scale as the Severn estuary (figure 14.8). In Argentina there are two sites: San José and Golfo Nuevo; Australia has the Walcott Inlet; the USA & Canada share the Bay of Fundy; Canada has Cobequid; India has the Gulf of Khambat; the USA has Turnagain Arm and Knik Arm; and Russia has Tugur.

And then there is the world's tidal whopper, a place called Penzhinsk in Russia with a resource of 22 GW – ten times as big as the Severn!

Kowalik (2004) estimates that worldwide, 40–80 GW of tidal power could be generated. Shared between 6 billion people, that comes to 0.16–0.32 kWh/d per person.

Wave

We can estimate the total extractable power from waves by multiplying the length of exposed coastlines (roughly 300 000 km) by the typical power per unit length of coastline (10 kW per metre): the raw power is thus about 3000 GW.

Assuming 10% of this raw power is intercepted by systems that are 50%-efficient at converting power to electricity, wave power could deliver 0.5 kWh/d per person.

Geothermal

According to D. H. Freeston of the Auckland Geothermal Institute, geothermal power amounted on average to about 4 GW, worldwide, in 1995 – which is 0.01 kWh/d per person.

If we assume that the MIT authors on p234 were right, and if we assume that the whole world is like America, then geothermal power offers 8 kWh/d per person.

Solar for energy crops

People get all excited about energy crops like jatropha, which, it's claimed, wouldn't need to compete with food for land, because it can be grown on wastelands. People need to look at the numbers before they get excited.

The numbers for jatropha are on p284. Even if *all* of Africa were completely covered with jatropha plantations, the power produced, shared between six billion people, would be 8 kWh/d per person (which is only one third of today's global oil consumption). You can't fix your oil addiction by switching to jatropha!

Let's estimate a bound on the power that energy crops could deliver for the whole world, using the same method we applied to Britain in Chapter 6: imagine taking all arable land and devoting it to energy crops. 18% of the world's land is currently arable or crop land – an area of 27 million km^2. That's 4500 m^2 per person, if shared between 6 billion. Assuming a power density of 0.5 W/m^2, and losses of 33% in processing and farming, we find that energy crops, fully taking over all agricultural land, would deliver 36 kWh/d per person. Now, maybe this is an underestimate since in figure 6.11 (p43) we saw that Brazilian sugarcane can deliver a power density of 1.6 W/m^2, three times bigger than I just assumed. OK, maybe energy crops from Brazil have some sort of future. But I'd like to move on to the last option.

Solar heaters, solar photovoltaics, and concentrating solar power

Solar thermal water heaters are a no-brainer. They will work almost everywhere in the world. China are world leaders in this technology. There's over 100 GW of solar water heating capacity worldwide, and more than half of it is in China.

Solar photovoltaics were technically feasible for Europe, but I judged them too expensive. I hope I'm wrong, obviously. It will be wonderful if the cost of photovoltaic power drops in the same way that the cost of computer power has dropped over the last forty years.

My guess is that in many regions, the best solar technology for electricity production will be the concentrating solar power that we discussed on pages 178 and 236. On those pages we already established that one billion people in Europe and North Africa could be sustained by country-sized solar power facilities in deserts near the Mediterranean; and that half a billion in North America could be sustained by Arizona-sized facilities in the deserts of the USA and Mexico. I'll leave it as an exercise for the reader to identify appropriate deserts to help out the other 4.5 billion people in the world.

Sheffield	28%
Edinburgh	30%
Manchester	31%
Cork	32%
London	34%
Cologne	35%
Copenhagen	38%
Munich	38%
Paris	39%
Berlin	42%
Wellington, NZ	43%
Seattle	46%
Toronto	46%
Detroit, MI	54%
Winnipeg	55%
Beijing 2403	55%
Sydney 2446	56%
Pula, Croatia	57%
Nice, France	58%
Boston, MA	58%
Bangkok, Thailand	60%
Chicago	60%
New York	61%
Lisbon, Portugal	61%
Kingston, Jamaica	62%
San Antonio	62%
Seville, Spain	66%
Nairobi, Kenya	68%
Johannesburg, SA	71%
Tel Aviv	74%
Los Angeles	77%
Upington, SA	91%
Yuma, AZ	93%
Sahara Desert	98%

Table 30.4. World sunniness figures. [3doaeg]

The bottom line

The non-solar numbers add up as follows. Wind: 24 kWh/d/p; hydro: 3.6 kWh/d/p; tide: 0.3 kWh/d/p; wave: 0.5 kWh/d/p; geothermal: 8 kWh/d/p – a total of 36 kWh/d/p. Our target was a post-European consumption of 80 kWh/d per person. We have a clear conclusion: the non-solar renewables may be "huge," but they are not huge enough. To

complete a plan that adds up, we must rely on one or more forms of solar power. Or use nuclear power. Or both.

Notes and further reading

page no.

234 *North American offshore wind resources.*
`www.ocean.udel.edu/windpower/ResourceMap/index-wn-dp.html`

235 *North America needs solar in its own deserts, or nuclear power, or both.* To read Google's 2008 plan for a 40% defossilization of the USA, see Jeffery Greenblatt's article *Clean Energy 2030* [`3lcw9c`]. The main features of this plan are efficiency measures, electrification of transport, and electricity production from renewables. Their electricity production plan includes

10.6 kWh/d/p	of wind power,
2.7 kWh/d/p	of solar photovoltaic,
1.9 kWh/d/p	of concentrating solar power,
1.7 kWh/d/p	of biomass,
and 5.8 kWh/d/p	of geothermal power

by 2030. That's a total of 23 kWh/d/p of new renewables. They also assume a small increase in nuclear power from 7.2 kWh/d/p to 8.3 kWh/d/p, and no change in hydroelectricity. Natural gas would continue to be used, contributing 4 kWh/d/p.

237 *The world's total hydro potential...*
Source: `www.ieahydro.org/faq.htm`.

– *Global coastal wave power resource is estimated to be 3000 GW.*
See Quayle and Changery (1981).

– *Geothermal power in 1995.* Freeston (1996).

238 *Energy crops.* See Rogner (2000) for estimates similar to mine.

Further reading: *Nature* magazine has an 8-page article discussing how to power the world (Schiermeier et al., 2008).

31 The last thing we should talk about

Capturing carbon dioxide from thin air is the last thing we should talk about.

When I say this, I am deliberately expressing a double meaning. First, the energy requirements for carbon capture from thin air are so enormous, it seems almost absurd to talk about it (and there's the worry that raising the possibility of fixing climate change by this sort of geoengineering might promote inaction today). But second, I do think we should talk about it, contemplate how best to do it, and fund research into how to do it better, because capturing carbon from thin air may turn out to be our last line of defense, if climate change is as bad as the climate scientists say, and if humanity fails to take the cheaper and more sensible options that may still be available today.

Before we discuss capturing carbon from thin air, we need to understand the global carbon picture better.

Understanding CO_2

When I first planned this book, my intention was to ignore climate change altogether. In some circles, "Is climate change happening?" was a controversial question. As were "Is it caused by humans?" and "Does it matter?" And, dangling at the end of a chain of controversies, "What should we do about it?" I felt that sustainable energy was a compelling issue by itself, and it was best to avoid controversy. My argument was to be: "Never mind when fossil fuels are going to run out; never mind whether climate change is happening; *burning fossil fuels is not sustainable anyway*; let's imagine living sustainably, and figure out how much sustainable energy is available."

However, climate change has risen into public consciousness, and it raises all sorts of interesting back-of-envelope questions. So I decided to discuss it a little in the preface and in this closing chapter. Not a complete discussion, just a few interesting numbers.

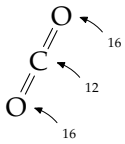


Figure 31.1. The weights of an atom of carbon and a molecule of CO_2 are in the ratio 12 to 44, because the carbon atom weighs 12 units and the two oxygen atoms weigh 16 each. $12 + 16 + 16 = 44$.

Units

Carbon pollution charges are usually measured in dollars or euros per ton of CO_2, so I'll use the *ton of CO_2* as the main unit when talking about per-capita carbon pollution, and the *ton of CO_2 per year* to measure rates of pollution. (The average European's greenhouse emissions are equivalent to 11 tons per year of CO_2; or 30 kg per day of CO_2.) But when talking about carbon in fossil fuels, vegetation, soil, and water, I'll talk about tons of carbon. One ton of CO_2 contains 12/44 tons of carbon, a bit more than a quarter of a ton. On a planetary scale, I'll talk about gigatons of carbon (Gt C). A gigaton of carbon is a billion tons. Gigatons are hard to imagine, but if you want to bring it down to a human scale, imagine burning one

ton of coal (which is what you might use to heat a house over a year). Now imagine everyone on the planet burning one ton of coal per year: that's 6 Gt C per year, because the planet has 6 billion people.

Where is the carbon?

Where is all the carbon? We need to know how much is in the oceans, in the ground, and in vegetation, compared to the atmosphere, if we want to understand the consequences of CO_2 emissions.

Figure 31.2 shows where the carbon is. Most of it – 40 000 Gt – is in the ocean (in the form of dissolved CO_2 gas, carbonates, living plant and

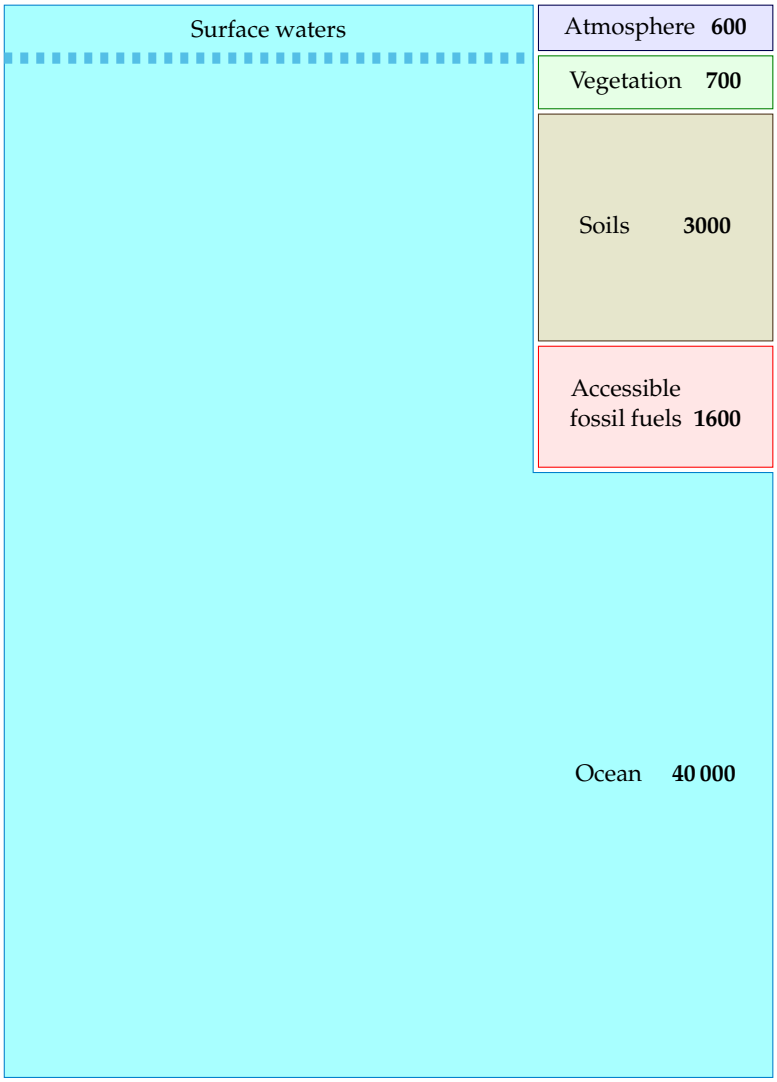


Figure 31.2. Estimated amounts of carbon, in gigatons, in accessible places on the earth. (There's a load more carbon in rocks too; this carbon moves round on a timescale of millions of years, with a long-term balance between carbon in sediment being subducted at tectonic plate boundaries, and carbon popping out of volcanoes from time to time. For simplicity I ignore this geological carbon.)

animal life, and decaying materials). Soils and vegetation together contain about 3700 Gt. Accessible fossil fuels – mainly coal – contain about 1600 Gt. Finally, the atmosphere contains about 600 Gt of carbon.

Until recently, all these pools of carbon were roughly in balance: all flows of carbon out of a pool (say, soils, vegetation, or atmosphere) were balanced by equal flows into that pool. The flows into and out of the fossil fuel pool were both negligible. Then humans started burning fossil fuels. This added two extra *unbalanced* flows, as shown in figure 31.3.

The rate of fossil fuel burning was roughly 1 Gt C/y in 1920, 2 Gt C/y in 1955, and 8.4 Gt C in 2006. (These figures include a small contribution from cement production, which releases CO_2 from limestone.)

How has this significant extra flow of carbon modified the picture shown in figure 31.2? Well, it's not exactly known. Figure 31.3 shows the key things that *are* known. Much of the extra 8.4 Gt C per year that we're putting into the atmosphere stays in the atmosphere, raising the atmospheric concentration of carbon-dioxide. The atmosphere equilibrates fairly rapidly with the surface waters of the oceans (this equilibration takes only five or ten years), and there is a net flow of CO_2 from the atmosphere into the surface waters of the oceans, amounting to 2 Gt C per year. (Recent research indicates this rate of carbon-uptake by the oceans may be reducing, however.) This unbalanced flow into the surface waters causes ocean acidification, which is bad news for coral. Some extra carbon is moving into vegetation and soil too, perhaps about 1.5 Gt C per year, but these flows are less well measured. Because roughly half of the carbon emissions are staying in the atmosphere, continued carbon pollution at a rate of 8.4 Gt C per year will continue to increase CO_2 levels in the atmosphere, and in the surface waters.

What is the long-term destination of the extra CO_2? Well, since the amount in fossil fuels is so much smaller than the total in the oceans, "in the long term" the extra carbon will make its way into the ocean, and the amounts of carbon in the atmosphere, vegetation, and soil will return to normal. However, "the long term" means thousands of years. Equilibration between atmosphere and the *surface* waters is rapid, as I said, but figures 31.2 and 31.3 show a dashed line separating the surface waters of the ocean from the rest of the ocean. On a time-scale of 50 years, this boundary is virtually a solid wall. Radioactive carbon dispersed across the globe by the atomic bomb tests of the 1960s and 70s has penetrated the oceans to a depth of only about 400 m. In contrast the average depth of the oceans is about 4000 m.

The oceans circulate slowly: a chunk of deep-ocean water takes about 1000 years to roll up to the surface and down again. The circulation of the deep waters is driven by a combination of temperature gradients and salinity gradients, so it's called the thermohaline circulation (in contrast to the circulations of the surface waters, which are wind-driven).

This slow turn-over of the oceans has a crucial consequence: we have

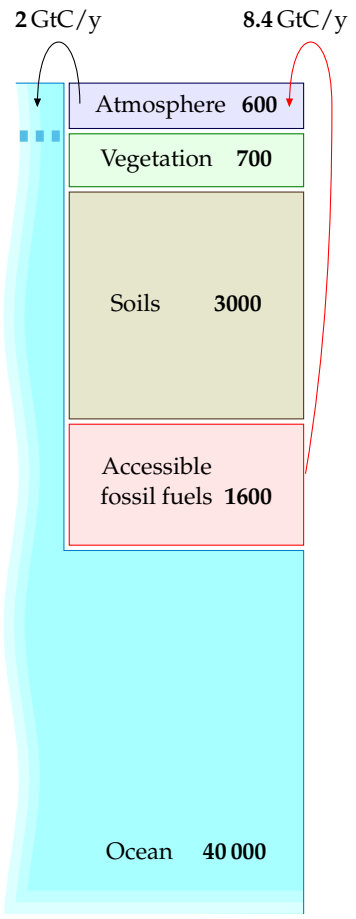


Figure 31.3. The arrows show two extra carbon flows produced by burning fossil fuels. There is an imbalance between the 8.4 Gt C/y emissions into the atmosphere from burning fossil fuels and the 2 Gt C/y take-up of CO_2 by the oceans. This cartoon omits the less-well quantified flows between atmosphere, soil, vegetation, and so forth.

enough fossil fuels to seriously influence the climate over the next 1000 years.

Where is the carbon going

Figure 31.3 is a gross simplification. For example, humans are causing additional flows not shown on this diagram: the burning of peat and forests in Borneo in 1997 alone released about 0.7 Gt C. Accidentally-started fires in coal seams release about 0.25 Gt C per year.

Nevertheless, this cartoon helps us understand roughly what will happen in the short term and the medium term under various policies. First, if carbon pollution follows a "business as usual" trajectory, burning another 500 Gt of carbon over the next 50 years, we can expect the carbon to continue to trickle gradually into the surface waters of the ocean at a rate of 2 Gt C per year. By 2055, at least 100 Gt of the 500 would have gone into the surface waters, and CO_2 concentrations in the atmosphere would be roughly double their pre-industrial levels.

If fossil-fuel burning were reduced to zero in the 2050s, the 2 Gt flow from atmosphere to ocean would also reduce significantly. (I used to imagine that this flow into the ocean would persist for decades, but that would be true only if the surface waters were out of equilibrium with the atmosphere; but, as I mentioned earlier, the surface waters and the atmosphere reach equilibrium within just a few years.) Much of the 500 Gt we put into the atmosphere would only gradually drift into the oceans over the next few thousand years, as the surface waters roll down and are replaced by new water from the deep.

Thus our perturbation of the carbon concentration might eventually be righted, but only after thousands of years. And that's assuming that this large perturbation of the atmosphere doesn't drastically alter the ecosystem. It's conceivable, for example, that the acidification of the surface waters of the ocean might cause a sufficient extinction of ocean plant-life that a new vicious cycle kicks in: acidification means extinguished plant-life, means plant-life absorbs less CO_2 from the ocean, means oceans become even more acidic. Such vicious cycles (which scientists call "positive feedbacks" or "runaway feedbacks") have happened on earth before: it's believed, for example, that ice ages ended relatively rapidly because of positive feedback cycles in which rising temperatures caused surface snow and ice to melt, which reduced the ground's reflection of sunlight, which meant the ground absorbed more heat, which led to increased temperatures. (Melted snow – water – is much darker than frozen snow.) Another positive feedback possibility to worry about involves methane hydrates, which are frozen in gigaton quantities in places like Arctic Siberia, and in 100-gigaton quantities on continental shelves. Global warming greater than 1 °C would possibly melt methane hydrates, which release methane into the atmosphere, and methane increases global warming more strongly

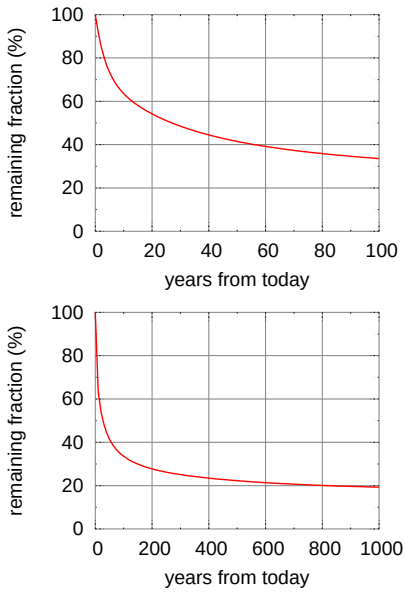


Figure 31.4. Decay of a small pulse of CO_2 added to today's atmosphere, according to the Bern model of the carbon cycle. Source: Hansen et al. (2007).

than CO_2 does.

This isn't the place to discuss the uncertainties of climate change in any more detail. I highly recommend the books *Avoiding Dangerous Climate Change* (Schellnhuber et al., 2006) and *Global Climate Change* (Dessler and Parson, 2006). Also the papers by Hansen et al. (2007) and Charney et al. (1979).

The purpose of this chapter is to discuss the idea of fixing climate change by sucking carbon dioxide from thin air; we discuss the energy cost of this sucking next.

The cost of sucking

Today, pumping carbon out of the ground is big bucks. In the future, perhaps pumping carbon *into* the ground is going to be big bucks. Assuming that inadequate action is taken now to halt global carbon pollution, perhaps a coalition of the willing will in a few decades pay to create a giant vacuum cleaner, and clean up everyone's mess.

Before we go into details of how to capture carbon from thin air, let's discuss the unavoidable energy cost of carbon capture. Whatever technologies we use, they have to respect the laws of physics, and unfortunately grabbing CO_2 from thin air and concentrating it requires energy. The laws of physics say that the energy required must be at least 0.2 kWh per kg of CO_2 (table 31.5). Given that real processes are typically 35% efficient at best, I'd be amazed if the energy cost of carbon capture is ever reduced below 0.55 kWh per kg.

Now, let's assume that we wish to neutralize a typical European's CO_2 output of 11 tons per year, which is 30 kg per day per person. The energy required, assuming a cost of 0.55 kWh per kg of CO_2, is 16.5 kWh per day per person. This is exactly the same as British electricity consumption. So powering the giant vacuum cleaner may require us to *double* our electricity production – or at least, to somehow obtain extra power equal to our current electricity production.

If the cost of running giant vacuum cleaners can be brought down, brilliant, let's make them. But no amount of research and development can get round the laws of physics, which say that grabbing CO_2 from thin air and concentrating it into liquid CO_2 requires at least 0.2 kWh per kg of CO_2.

Now, what's the best way to suck CO_2 from thin air? I'll discuss four technologies for building the giant vacuum cleaner:

A. chemical pumps;

B. trees;

C. accelerated weathering of rocks;

D. ocean nourishment.

A. Chemical technologies for carbon capture

The chemical technologies typically deal with carbon dioxide in two steps.

$$0.03\%\ CO_2 \xrightarrow{\text{concentrate}} \text{Pure } CO_2 \xrightarrow{\text{compress}} \text{Liquid } CO_2$$

First, they *concentrate* CO_2 from its low concentration in the atmosphere; then they *compress* it into a small volume ready for shoving somewhere (either down a hole in the ground or deep in the ocean). Each of these steps has an energy cost. The costs required by the laws of physics are shown in table 31.5.

	cost (kWh/kg)
concentrate	0.13
compress	0.07
total	0.20

Table 31.5. The inescapable energy-cost of concentrating and compressing CO_2 from thin air.

In 2005, the best published methods for CO_2 capture from thin air were quite inefficient: the energy cost was about 3.3 kWh per kg, with a financial cost of about $140 per ton of CO_2. At this energy cost, capturing a European's 30 kg per day would cost 100 kWh per day – almost the same as the European's energy consumption of 125 kWh per day. Can better vacuum cleaners be designed?

Recently, Wallace Broecker, climate scientist, "perhaps the world's foremost interpreter of the Earth's operation as a biological, chemical, and physical system," has been promoting an as yet unpublished technology developed by physicist Klaus Lackner for capturing CO_2 from thin air. Broecker imagines that the world could carry on burning fossil fuels at much the same rate as it does now, and 60 million CO_2-scrubbers (each the size of an up-ended shipping container) will vacuum up the CO_2. What energy does Lackner's process require? In June 2007 Lackner told me that his lab was achieving 1.3 kWh per kg, but since then they have developed a new process based on a resin that absorbs CO_2 when dry and releases CO_2 when moist. Lackner told me in June 2008 that, in a dry climate, the concentration cost has been reduced to about 0.18–0.37 kWh of low-grade heat per kg CO_2. The compression cost is 0.11 kWh per kg. Thus Lackner's total cost is 0.48 kWh or less per kg. For a European's emissions of 30 kg CO_2 per day, we are still talking about a cost of 14 kWh per day, of which 3.3 kWh per day would be electricity, and the rest heat.

Hurray for technical progress! But please don't think that this is a *small* cost. We would require roughly a 20% increase in world energy production, just to run the vacuum cleaners.

B. What about trees?

Trees are carbon-capturing systems; they suck CO_2 out of thin air, and they don't violate any laws of physics. They are two-in-one machines: they are carbon-capture facilities powered by built-in solar power stations. They capture carbon using energy obtained from sunlight. The fossil fuels that we burn were originally created by this process. So, the suggestion is, how about trying to do the opposite of fossil fuel burning? How about creating

wood and burying it in a hole in the ground, while, next door, humanity continues digging up fossil wood and setting fire to it? It's daft to imagine creating buried wood at the same time as digging up buried wood. Even so, let's work out the land area required to solve the climate problem with trees.

The best plants in Europe capture carbon at a rate of roughly 10 tons of dry wood per hectare per year – equivalent to about 15 tons of CO_2 per hectare per year – so to fix a European's output of 11 tons of CO_2 per year we need 7500 square metres of forest per person. This required area of 7500 square metres per person is *twice the area of Britain* per person. And then you'd have to find somewhere to permanently store 7.5 tons of wood per person per year! At a density of 500 kg per m^3, each person's wood would occupy 15 m^3 per year. A lifetime's wood – which, remember, must be safely stored away and never burned – would occupy 1000 m^3. That's five times the entire volume of a typical house. If anyone proposes using trees to undo climate change, they need to realise that country-sized facilities are required. I don't see how it could ever work.

1 hectare = 10 000 m^2

C. Enhanced weathering of rocks

Is there a sneaky way to avoid the significant energy cost of the chemical approach to carbon-sucking? Here is an interesting idea: pulverize rocks that are capable of absorbing CO_2, and leave them in the open air. This idea can be pitched as the acceleration of a natural geological process. Let me explain.

Two flows of carbon that I omitted from figure 31.3 are the flow of carbon from rocks into oceans, associated with the natural weathering of rocks, and the natural precipitation of carbon into marine sediments, which eventually turn back into rocks. These flows are relatively small, involving about 0.2 Gt C per year (0.7 Gt CO_2 per year). So they are dwarfed by current human carbon emissions, which are about 40 times bigger. But the suggestion of enhanced-weathering advocates is that we could fix climate change by speeding up the rate at which rocks are broken down and absorb CO_2. The appropriate rocks to break down include olivines or magnesium silicate minerals, which are widespread. The idea would be to find mines in places surrounded by many square kilometres of land on which crushed rocks could be spread, or perhaps to spread the crushed rocks directly on the oceans. Either way, the rocks would absorb CO_2 and turn into carbonates and the resulting carbonates would end up being washed into the oceans. To pulverized the rocks into appropriately small grains for the reaction with CO_2 to take place requires only 0.04 kWh per kg of sucked CO_2. Hang on, isn't that smaller than the 0.20 kWh per kg required by the laws of physics? Yes, but nothing is wrong: the rocks themselves are the sources of the missing energy. Silicates have higher energy than carbonates, so the rocks pay the energy cost of sucking the CO_2 from thin

air.

I like the small energy cost of this scheme but the difficult question is, who would like to volunteer to cover their country with pulverized rock?

D. Ocean nourishment

One problem with chemical methods, tree-growing methods, and rock-pulverizing methods for sucking CO_2 from thin air is that all would require a lot of work, and no-one has any incentive to do it – unless an international agreement pays for the cost of carbon capture. At the moment, carbon prices are too low.

A final idea for carbon sucking might sidestep this difficulty. The idea is to persuade the ocean to capture carbon a little faster than normal as a by-product of fish farming.

Some regions of the world have food shortages. There are fish shortages in many areas, because of over-fishing during the last 50 years. The idea of *ocean nourishment* is to fertilize the oceans, supporting the base of the food chain, enabling the oceans to support more plant life and more fish, and incidentally to fix more carbon. Led by Australian scientist Ian Jones, the ocean nourishment engineers would like to pump a nitrogen-containing fertilizer such as urea into appropriate fish-poor parts of the ocean. They claim that 900 km^2 of ocean can be nourished to take up about 5 Mt CO_2/y. Jones and his colleagues reckon that the ocean nourishment process is suitable for any areas of the ocean deficient in nitrogen. That includes most of the North Atlantic. Let's put this idea on a map. UK carbon emissions are about 600 Mt CO_2/y. So complete neutralization of UK carbon emissions would require 120 such areas in the ocean. The map

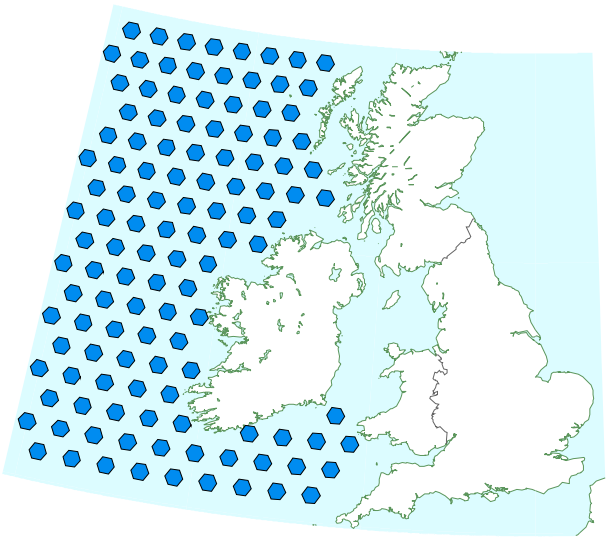
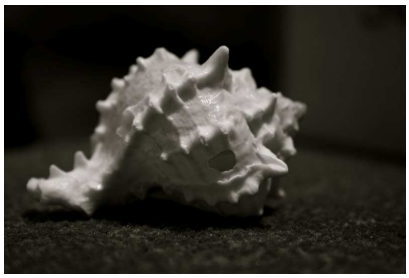


Figure 31.6. 120 areas in the Atlantic Ocean, each 900 km^2 in size. These make up the estimated area required in order to fix Britain's carbon emissions by ocean nourishment.

in figure 31.6 shows these areas to scale alongside the British Isles. As usual, a plan that actually adds up requires country-sized facilities! And we haven't touched on how we would make all the required urea.

While it's an untested idea, and currently illegal, I do find ocean nourishment interesting because, in contrast to geological carbon storage, it's a technology that might be implemented even if the international community doesn't agree on a high value for cleaning up carbon pollution; fishermen might nourish the oceans purely in order to catch more fish.

> *Commentators can be predicted to oppose manipulations of the ocean, focusing on the uncertainties rather than on the potential benefits. They will be playing to the public's fear of the unknown. People are ready to passively accept an escalation of an established practice (e.g., dumping CO_2 in the atmosphere) while being wary of innovations that might improve their future well being. They have an uneven aversion to risk.*
>
> Ian Jones



> *We, humanity, cannot release to the atmosphere all, or even most, fossil fuel CO_2. To do so would guarantee dramatic climate change, yielding a different planet...*
>
> J. Hansen et al (2007)

> *"Avoiding dangerous climate change" is impossible – dangerous climate change is already here. The question is, can we avoid* **catastrophic** *climate change?*
>
> David King, UK Chief Scientist, 2007

Notes

page no.

240 *climate change ... was a controversial question.* Indeed there still is a "yawning gap between mainstream opinion on climate change among the educated elites of Europe and America" [voxbz].

241 *Where is the carbon?* Sources: Schellnhuber et al. (2006), Davidson and Janssens (2006).

242 *The rate of fossil fuel burning...* Source: Marland et al. (2007).

– *Recent research indicates carbon-uptake by the oceans may be reducing.* www.timesonline.co.uk/tol/news/uk/science/article1805870.ece, www.sciencemag.org/cgi/content/abstract/1136188, [yofchc], Le Quéré et al. (2007).

– *roughly half of the carbon emissions are staying in the atmosphere.* It takes 2.1 billion tons of carbon in the atmosphere (7.5 Gt CO_2) to raise the atmospheric CO_2 concentration by one part per million (1 ppm). If all the CO_2 we pumped into the atmosphere stayed there, the concentration would be rising by more than 3 ppm per year – but it is actually rising at only 1.5 ppm per year.

– *Radioactive carbon ... has penetrated to a depth of only about 400 m.* The mean value of the penetration depth of bomb ^{14}C for all observational sites during the late 1970s is 390±39 m (Broecker et al., 1995). From [3e28ed].

244 *Global warming greater than 1 °C would possibly melt methane hydrates.* Source: Hansen et al. (2007, p1942).

245 *Table 31.5. Inescapable cost of concentrating and compressing CO_2 from thin air.* The unavoidable energy requirement to concentrate CO_2 from 0.03% to 100% at atmospheric pressure is $kT \ln 100/0.03$ per molecule, which is 0.13 kWh per kg. The ideal energy cost of compression of CO_2 to 110 bar (a pressure mentioned for geological storage) is 0.067 kWh/kg. So the total ideal cost of CO_2 capture and compression is 0.2 kWh/kg. According to the IPCC special report on carbon capture and storage, the practical cost of the second step, compression of CO_2 to 110 bar, is 0.11 kWh per kg. (0.4 GJ per t CO_2; 18 kJ per mole CO_2; 7 kT per molecule.)

245 *Shoving the CO_2 down a hole in the ground or deep in the ocean.* See Williams (2000) for discussion. "For a large fraction of injected CO_2 to remain in the ocean, injection must be at great depths. A consensus is developing that the best near-term strategy would be to discharge CO_2 at depths of 1000–1500 metres, which can be done with existing technology."
See also the Special Report by the IPCC: `www.ipcc.ch/ipccreports/srccs.htm`.

– *In 2005, the best methods for carbon capture were quite inefficient: the energy cost was about 3.3 kWh per kg, with a financial cost of about $140 per ton of CO_2.* Sources: Keith et al. (2005), Lackner et al. (2001), Herzog (2003), Herzog (2001), David and Herzog (2000).

– *Wallace Broecker, climate scientist...* `www.af-info.or.jp/eng/honor/hot/enrbro.html`. His book promoting artificial trees: Broecker and Kunzig (2008).

246 *The best plants in Europe capture carbon at a rate of roughly 10 tons of dry wood per hectare per year.* Source: Select Committee on Science and Technology.

– *Enhanced weathering of rocks.* See Schuiling and Krijgsman (2006).

247 *Ocean nourishment.* See Judd et al. (2008). See also Chisholm et al. (2001). The risks of ocean nourishment are discussed in Jones (2008).

32 Saying yes

Because Britain currently gets 90% of its energy from fossil fuels, it's no surprise that getting off fossil fuels requires big, big changes – a total change in the transport fleet; a complete change of most building heating systems; and a 10- or 20-fold increase in green power.

Given the general tendency of the public to say "no" to wind farms, "no" to nuclear power, "no" to tidal barrages – "no" to anything other than fossil fuel power systems – I am worried that we won't actually get off fossil fuels when we need to. Instead, we'll settle for half-measures: slightly-more-efficient fossil-fuel power stations, cars, and home heating systems; a fig-leaf of a carbon trading system; a sprinkling of wind turbines; an inadequate number of nuclear power stations.

We need to choose a plan that adds up. It *is* possible to make a plan that adds up, but it's not going to be easy.

We need to stop saying no and start saying yes. We need to stop the Punch and Judy show and get building.

If you would like an honest, realistic energy policy that adds up, please tell all your political representatives and prospective political candidates.

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